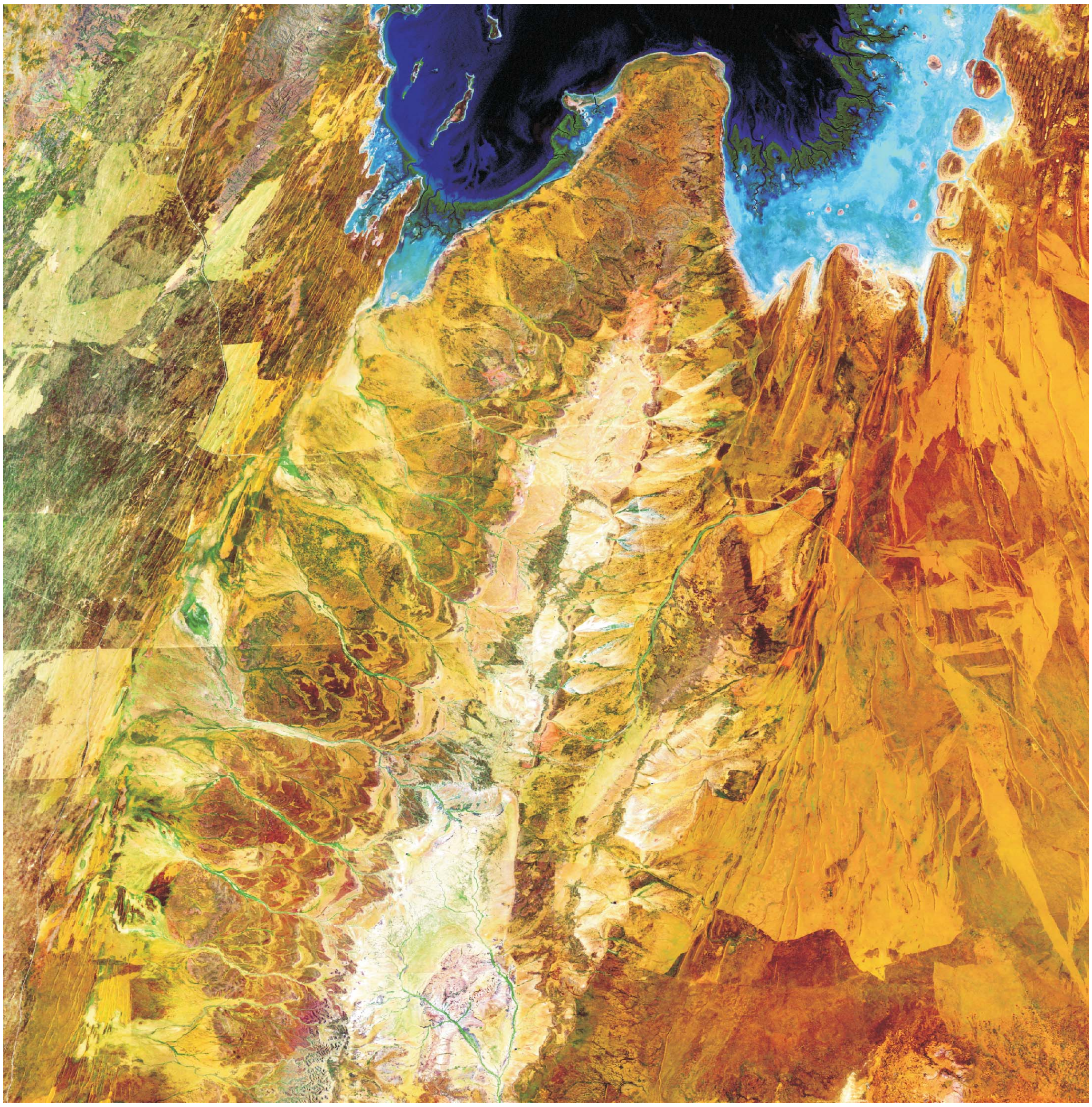
REPORT 52

GOVERNMENT OF WESTERN AUSTRALIA

STRUCTURAL INTERPRETATION AND HYDROCARBON POTENTIAL OF THE GIRALIA AREA, CARNARVON BASIN

by A. Crostella and R. P. Iasky



GEOLOGICAL SURVEY OF WESTERN AUSTRALIA

DEPARTMENT OF MINERALS AND ENERGY

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STRUCTURAL INTERPRETATION AND HYDROCARBON POTENTIAL OF THE GIRALIA AREA, CARNARVON BASIN

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MINISTER FOR MINES
The Hon. Norman Moore, MLC

DIRECTOR GENERAL
L. C. Ranford

ACTING DIRECTOR, GEOLOGICAL SURVEY OF WESTERN AUSTRALIA
David Blight

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Landsat Thematic Mapper RGB-741 (11.1.1995) image of the Giralia Anticline, Western Australia

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Structural interpretation and hydrocarbon potential of the Giralia area, Carnarvon Basin

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Abstract

The northernmost part of the Southern Carnarvon Basin, here referred to as the Giralia area, is characterized by three Middle Miocene anticlines: the Rough Range, Giralia, and Marrilla Anticlines. The drilled succession in the area consists of Devonian – Lower Carboniferous rocks covered by Upper Carboniferous – Permian rocks, and Lower Triassic rocks in the northern part. A thin cover of Cretaceous–Tertiary sedimentary rocks unconformably overlie older rocks. Seismic data indicate that the breakup of Australia from greater India during the Early Cretaceous had the greatest impact on the structural evolution of the area. This tectonism produced wrenching that resulted in long-wavelength folds and strike-slip faults. The newly interpreted Cardabia Transfer Fault is a significant strike-slip fault, which is visible on gravity images and is taken to represent the northern limit of the Gascoyne Platform.

There have been only a few valid tests for hydrocarbon plays in the Giralia area. Lower Cretaceous sandstones have been the main objective for oil exploration in the Carnarvon Basin, but in the Giralia area this potential reservoir is either too remote from effective source rocks, or without adequate seal. Permian source rocks are regionally immature to marginally mature whereas Devonian–Silurian source rocks have been shown to have good potential for hydrocarbon generation. The Cretaceous succession still offers some potential for an oil discovery, whereas the Devonian succession offers the most challenging, yet untested, objective. The Salt Marsh anticlines in the southern part of the Giralia area can be compared to the anticlines in the northern part and could also be considered as possible traps for Devonian targets.

KEYWORDS: oil wells, hydrocarbons, seismic surveys, gravity, Southern Carnarvon Basin, Giralia, petroleum, anticlines, Western Australia, source rock

Introduction

The aim of this report is to produce a regional structural interpretation, analyse the drilling results of petroleum exploration wells drilled before 1996, and evaluate the hydrocarbon potential of the Giralia area. The Giralia area lies at the northernmost tip of the Southern Carnarvon Basin (Fig. 1), as presently defined (Hocking, 1994), where Upper Carboniferous – Lower Triassic strata overlie Devonian – Lower Carboniferous rocks. Oil exploration activities in the Giralia area commenced in 1947 when Ampol Exploration took out exploration permits over the entire Carnarvon Basin. In the Giralia area, 15 oil exploration wells have been drilled and eight seismic surveys of variable quality have been carried out with a total recording of 2482 line kilometres. Oil was detected from analyses of fluid inclusions within the Moogooloo Sandstone in wells Giralia 1 and Remarkable Hill 1 (Eadington, 1997). Indications of hydrocarbons were also detected in Gnaraloo 1 and Whitlock Dam 1.

Three sedimentary megasequences are recognized in the Giralia area: Devonian – Lower Carboniferous, Upper Carboniferous – Lower Triassic, and Cretaceous–Tertiary (Table 1). Devonian – Lower Carboniferous sedimentary rocks were deposited over large tracts of the entire Carnarvon Basin but are under-explored and poorly known. The Upper Carboniferous – Lower Triassic succession of the Giralia area represents a northwestward extension of the Merlinleigh Sub-basin, which contains Upper Carboniferous – Permian sedimentary rocks of the same depositional environment. The youngest sedimentary cycle is Cretaceous–Tertiary in age and gradually thickens to the west. The regional geology of the Giralia area was discussed in the general context of the Carnarvon Basin by Hocking et al. (1987). Other more specific work in the area has been reported, such as that of Condon et al. (1956), but no recent published review focuses on the Giralia area. Relevant information, however, is provided by papers dealing with neighbouring geological provinces, namely the review of the Carnarvon Terrace by Baillie and

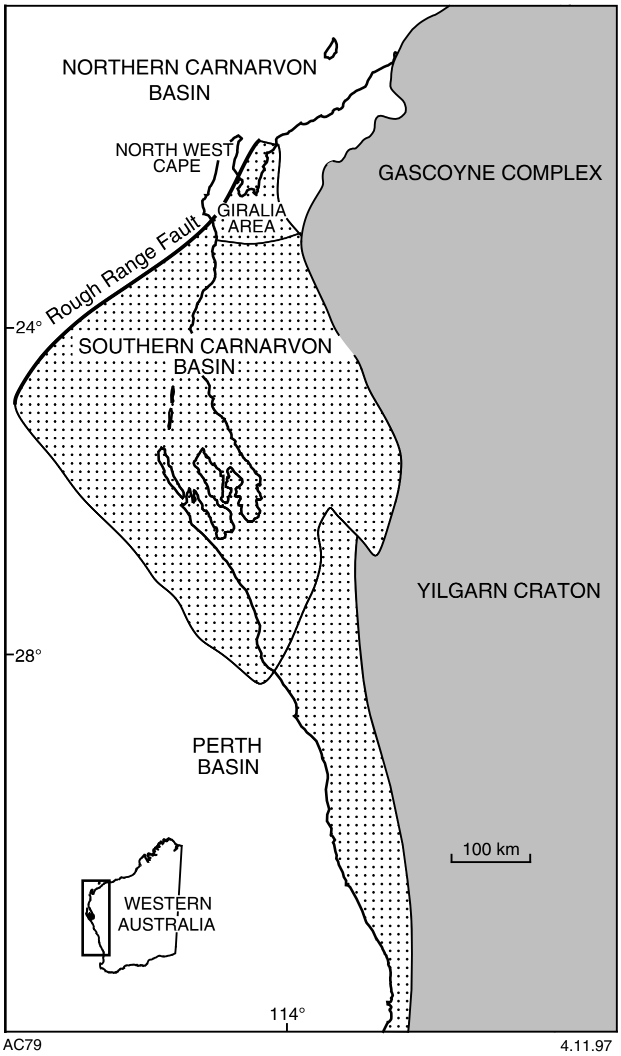


Figure 1. Locality map showing the main regional subdivisions (after Hocking, 1994)

Jacobson (1995); the synthesis of the North West Cape area by Malcolm et al. (1991); the review of the inner Barrow Sub-basin by Kopsen and McGann (1985); and recent Geological Survey of Western Australia (GSWA) studies (Crostella, 1995, 1996a,b).

Apart from the published material, data have been utilized from petroleum exploration well completion reports (Appendix 1), updated well formation tops (Appendix 2), seismic sections (Appendix 3), water bores penetrating the pre-Cretaceous section (Appendix 4), and the Palaeozoic section below the Rough Range Fault (Table 2).

Regional framework

Stratigraphy

A detailed description of the stratigraphy and environment of deposition of the three sedimentary megasequences (Table 1) is provided by Hocking et al. (1987).

Basement

In the Giralia area, three wells have reached phyllitic schist basement: Garden Mill 1, Yanrey 1, and Tent Hill 1. The three wells are located on the Yanrey Ridge (Fig. 2), which represents the western extension of the Precambrian Gascoyne Complex.

A CRA Exploration (CRAE) mineral exploration hole (M85–RH1) drilled near the Mia Mia water bores (Fig. 2) was also tentatively considered to have reached granitic basement (Gregory, 1982). The major components of the rock chips after separation from the drilling mud were described as ‘micaceous sandy mudstone’ and ‘subangular to subrounded quartz grains’. Although CRAE interpreted the mudstone fragments as contamination from higher up the hole, on lithological grounds it is here considered more likely that this well bottomed in the Permian Lyons Group, as the description includes metamorphic pebbles and boulders typical of that unit.

Devonian – Lower Carboniferous megasequence

The oldest sedimentary rocks penetrated in the Giralia area are Devonian carbonates and clastics in Rough Range 1 (Fig. 3).

Marrilla 1 was terminated in a carbonate unit that West Australian Petroleum (WAPET) tentatively referred to as the Silurian Dirk Hartog Limestone. This unit can also be interpreted as Devonian or Early Carboniferous, as the completion report does not provide evidence of a Silurian age. All other wells that penetrated pre-Permian units in the region, namely Rough Range 1, East Marrilla 1, Quail 1, and Gnaraloo 1, intersected Lower Carboniferous rocks; Marrilla 1, therefore, would be the only exception. Within the northern Peedamullah Shelf, all wells that reached basement encountered Devonian – Lower Carboniferous rocks with no evidence of older sedimentary rocks.

Cretaceous rocks rest unconformably on Silurian deposits only in the southern part of the Gascoyne Platform. It is concluded that the pre-Cretaceous limestone at the base of Marrilla 1 is, in fact, part of the Devonian – Lower Carboniferous succession.

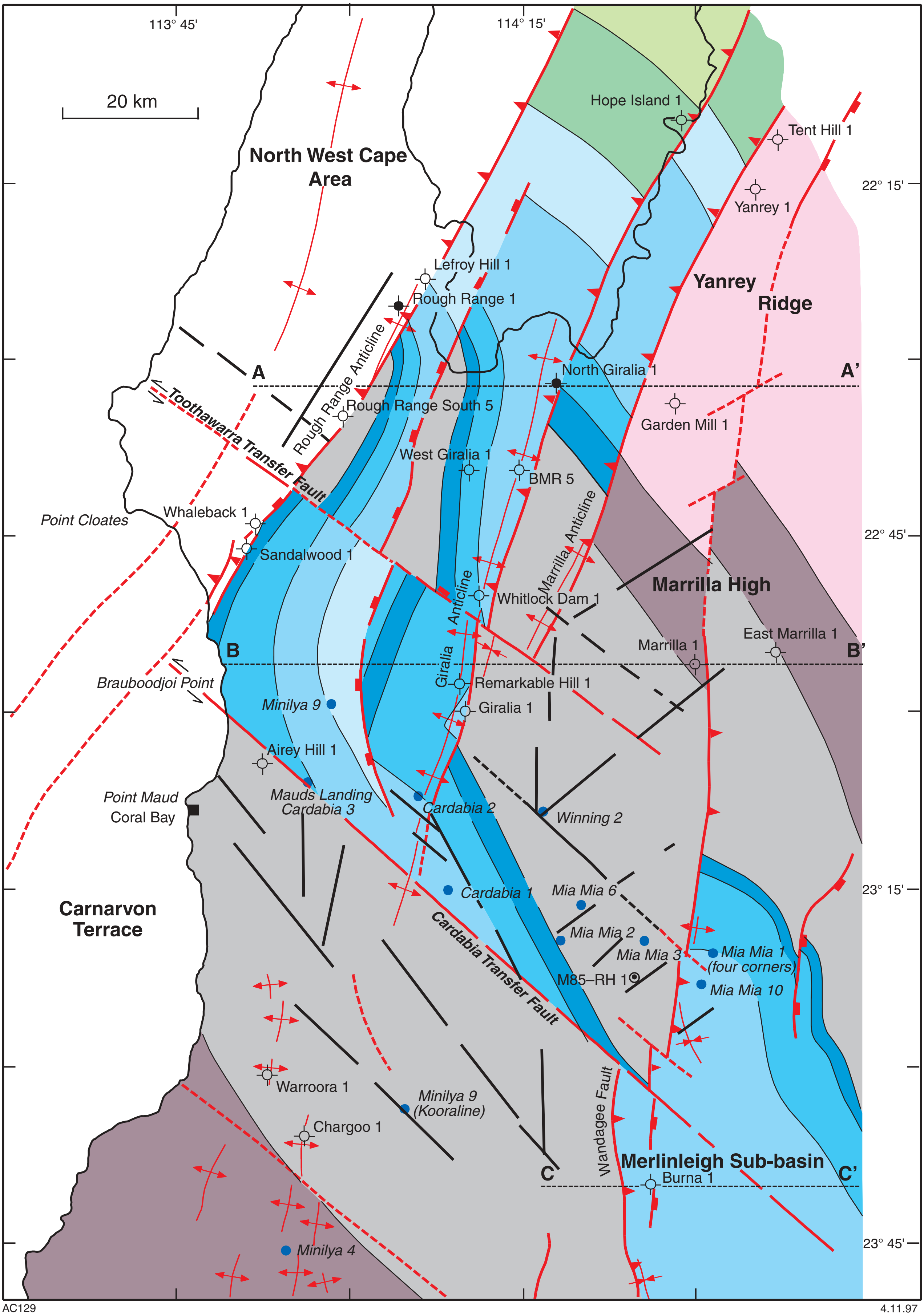
The Devonian – Lower Carboniferous megasequence (Table 1) comprises several siliciclastic and carbonate units, namely (in ascending order) the Nannyarra Sandstone, Gneudna Formation, Munabia Sandstone, Willaraddie Formation, Moogooree Limestone, and Yindagindy Formation. The latter unit is, at least in part, time-equivalent to the Quail Formation in the western part of the Merlinleigh Sub-basin. Within the framework of the GSWA Petroleum Exploration Initiatives program, the significance of the Upper Devonian – Lower Carboniferous units to hydrocarbon exploration in the Carnarvon Basin has been discussed by Crostella (1995). The Frasnian Gneudna Formation possesses some potential for oil generation (Ghori, 1996; Mory, 1996). The source rock potential of the unit is to be further evaluated at two locations in the Gascoyne Platform. The reservoir characteristics of the unit have yet to be qualified,

Table 1. Generalized stratigraphy of the Giralia area

Age	*Formation*	*Sedimentary sequences*	*Tectonic framework*	*Mapped seismic horizons*
MIDDLE MIOCENE	~ ~		Strike-slip faults anticlines ~ ~ ~ ~	
TERTIARY ↑ CRETACEOUS	Trealla Limestone (Tt) Cape Range Group (TC) Giralia Calcarenite (Tg) Cardabia Calcarenite (Tc) Korojon Calcarenite (Kk) Toolonga Calcilutite (Kt) Gearle Siltstone (KWg) Windalia Radiolarite (KWw) Muderong Shale (KWm) Birdrong Sandstone (Kwb)	Megasequence 3	Passive continental margin	Seismic horizon (Fig. 13) Seismic horizon (Fig. 14)
~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~	~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~	~Main Unconformity ~ ~	Breakup (strike-slip faults, anticlines) ~ ~ ~	Seismic horizon (Fig. 15)
EARLY TRIASSIC ↑ PERMIAN LATE CARBONIFEROUS	Mungaroo Formation (Rm) Locker Shale (Rl) Kennedy Group (PK) Byro Group (PB) Wooramel Group (PW) Callytharra Formation (Pc) Lyons Group (CPL)	Megasequence 2	Rift valley	Seismic horizon (Fig. 16)
~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~	~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~	Rifting ~ ~ ~ ~ ~ ~	~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~	
EARLY CARBONIFEROUS ↑ DEVONIAN	Quail Formation (Cq) Yindagindy Formation (Cy) Moogooree Limestone (Cm) Willaraddie Formation (Dw) Munabia Sandstone (Dm) Gneudna Formation (Dg) Nannyarra Sandstone (Dn)	Megasequence 1	Intracratonic basin	

Table 2. Permian lithostratigraphy of the Rough Range Trend

Well	*Depth (m)*	*Unit*	*Penetrated thickness (m) of pre-main unconformity Mesozoic units*
Lefroy Hill 1	1 486–1 512	(probably) Kennedy Group	82
Rough Range 1 (Backhouse, 1996a)	1 897–3 263	Lyons Group	788
Rough Range South 5 (Backhouse, 1996b)	1 386–1 451	Lyons Group	9
Whaleback 1	1 437–1 440.5 (core 11)	(likely) Callytharra Formation or Upper Lyons Group	216
Sandalwood 1	1 234–1 350	Lower Coolkilya Sandstone (Kennedy Group) or possibly uppermost Byro Group	46


113° 45'
114° 15'
20 km
North West Cape Area
Hope Island 1
Tent Hill 1
Yanrey 1
22° 15'
Lefroy Hill 1
Rough Range 1
Yanrey Ridge
Rough Range Anticline
North Giralia 1
A
A'
Toothawarra Transfer Fault
Rough Range South 5
Garden Mill 1
West Giralia 1
BMR 5
Point Cloates
Whaleback 1
22° 45'
Sandalwood 1
Marrilla Anticline
Marrilla High
Giralia Anticline
Whitlock Dam 1
East Marrilla 1
Marrilla 1
B
B'
Brauboodjoi Point
Remarkable Hill 1
Minilya 9
Giralia 1
Airey Hill 1
Point Maud
Coral Bay
Mauds Landing
Cardabia 3
Cardabia 2
Winning 2
Carnarvon Terrace
Cardabia 1
Mia Mia 6
23° 15'
Cardabia Transfer Fault
Mia Mia 2
Mia Mia 3
Mia Mia 1 (four corners)
M85–RH 1
Mia Mia 10
Warroora 1
Minilya 9 (Kooraline)
Chargoo 1
Wandagee Fault
C
Merlinleigh Sub-basin
C'
Burna 1
23° 45'
Minilya 4
AC129
4.11.97

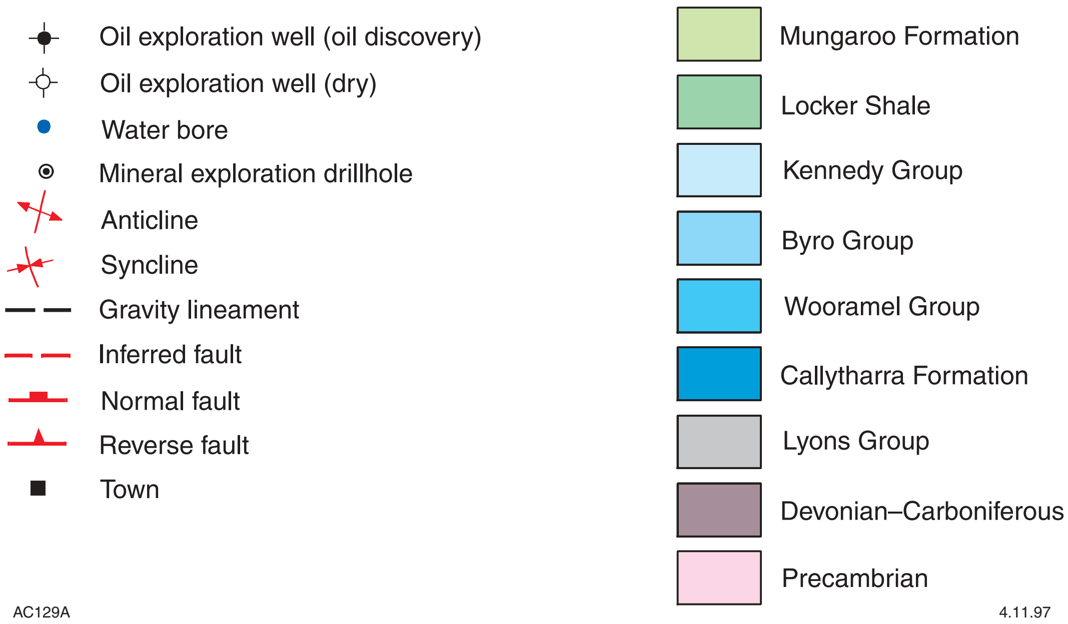


Figure 2. Regional pre-Cretaceous subcrop map of the Giralia area. The faults shown as reverse indicate the movement at breakup, although their Palaeozoic movement was normal. Sections A–A′, B–B′, and C–C′ are shown in Figure 20

although Frasnian reefs are present in the Canning Basin, and in the offshore Southern Carnarvon Basin (Carnarvon Terrace) where Geary (1970) identified a reef facies complex in Pendock 1. Terrigenous clastic sands of the Nannyarra and Munabia Sandstones and the Willaraddie and Yindagindy Formations offer good potential reservoirs, and seals may be provided by finer clastic rocks or impervious limestones. In the Giralia area, a specific study has not been carried out on this megasequence.

Upper Carboniferous – Lower Triassic megasequence

The thick Upper Carboniferous – Lower Triassic megasequence was deposited as a transgressive unit over the Lower Carboniferous succession. In relation to this transgression, no marked angular unconformity is discernible on seismic sections. Subsurface data indicate that the Upper Carboniferous – Permian succession was deposited uninterrupted, northwestward from the Merlinleigh Sub-basin to the Giralia area (Fig. 2). The lithostratigraphy of the two provinces is directly comparable (Fig. 4), comprising, in ascending order, the Lyons Group, the Callytharra Formation, three formations of the Wooramel Group (Cordalia Sandstone, Moogooloo Sandstone, and Billidee Formation), the Byro Group with its eight formations, and the Kennedy Group. The Kennedy Group is represented in the Merlinleigh Sub-basin and in the main Giralia area by the Coolkilya Sandstone, Mungadan Sandstone, and Binthalya Formation. In the Hope Island – Onslow area the group is undifferentiated apart from the uppermost Chinty Formation (Mory and Backhouse, 1997). It is conceivable that progressively younger units were deposited towards the northwest in a deeper, or deepening, rift valley. The general northward deepening of the basin is supported both in the Byro Sub-basin where the youngest deposits are the lower Byro Group, and in the Merlinleigh Sub-basin where the Kennedy Group overlies a full succession of the Byro Group. In the structurally high region drilled by Remarkable Hill 1 and Giralia 1, uppermost Permian and basal Triassic sediments were probably deposited but have been subsequently eroded (Fig. 5). In the northwestern part of the Giralia area, the Lower Triassic Locker Shale and Mungaroo Formation appear to conformably or slightly disconformably overlie Permian strata (Parry and Smith, 1988).

Source rocks have been identified in the Wooramel Group of the Merlinleigh Sub-basin (Crostella, 1995; Ghori, 1996). In that sub-basin the group ranges from over-mature in Kennedy Range 1, to mature along the western margin of the basin, to immature on the eastern margin. Data from the Giralia area (Giralia 1, Sandalwood 1, and Remarkable Hill 1) indicate that the Wooramel Group is immature to marginally mature in the area. It appears that the unit was never deeply buried because of the locally reduced thickness of the Byro and Kennedy Groups to the north and west. It is possible that the Wooramel Group becomes mature for the generation of hydrocarbons to the northwest where a thick Mesozoic succession was deposited. Good potential reservoirs may be present in the Moogooloo Sandstone (Havord, in prep.), and both the Billidee Formation and the basal Byro Group may provide a suitable seal. However, because of the low level of maturity the Upper Carboniferous – Permian megasequence in the Giralia area is not attractive to oil exploration companies.

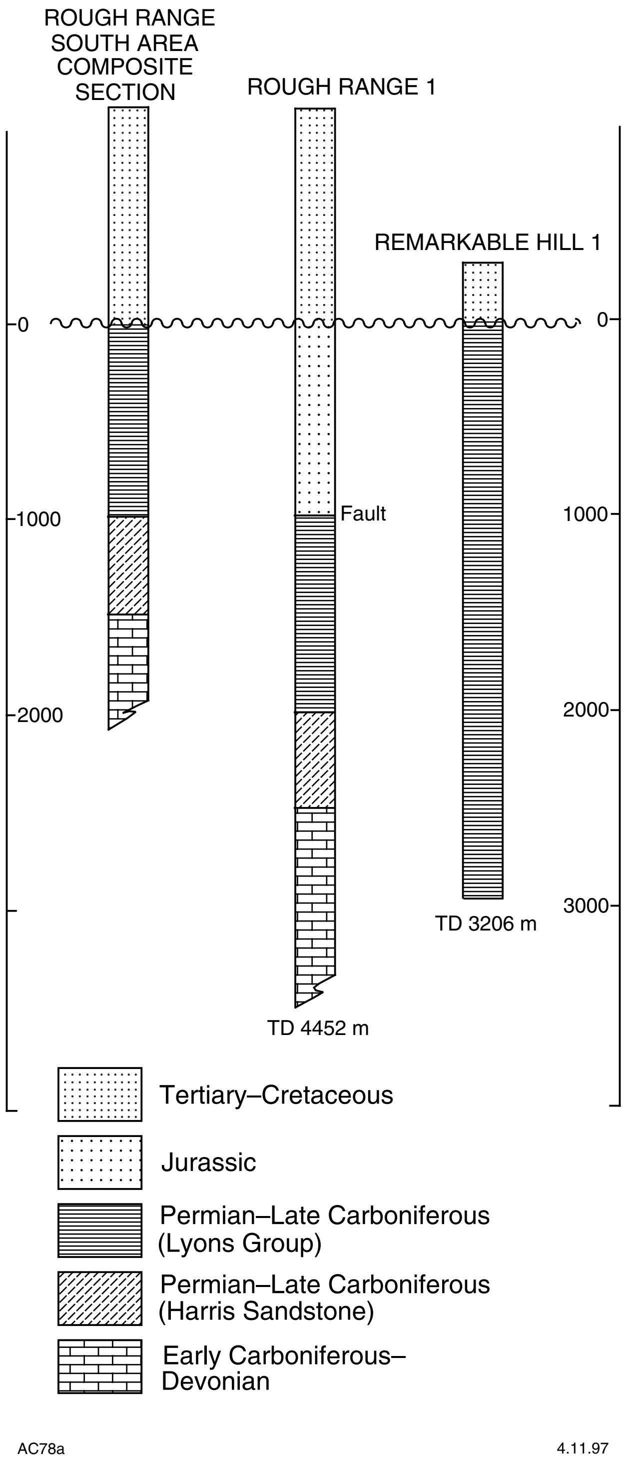


Figure 3. Depth to Devonian – Lower Carboniferous in the Rough Range area

Cretaceous–Tertiary megasequence

The third megasequence comprises Cretaceous–Tertiary clastics and carbonates. In a large part of the Giralia area the megasequence is transgressive, with a marked angular unconformity over Permian sedimentary rocks (Figs 5, 6, and 7). This angular unconformity may be termed the 'Main Unconformity' and indicates that significant tectonism predated the Early Neocomian transgression. The angularity is clearly visible on seismic sections at the base of the Cretaceous–Tertiary megasequence. This sequence is little more than a veneer in the east, whereas it thickens to about 1200 m in the west. The basal Birdrong Sandstone has been considered an attractive objective for oil exploration because it has very good reservoir potential for hydrocarbons and is overlain by regional sealing units.

Structure

The structural setting of the Giralia area was assessed using several sources of information:

- surface geology (Condon et al., 1956; Hocking et al., 1985; van de Graaff et al., 1980);
- imaging of Bouguer gravity anomalies (Fig. 8);
- imaging of first vertical derivative of Bouguer gravity anomalies (Fig. 9);
- seismic sections (Appendix 3 and Figs 5 to 7, 10 to 12);
- interpretation of seismic horizons shown in Table 1 (Figs 13 to 16);
- regional pre-Cretaceous subcrop map (Fig. 2) constructed from petroleum exploration well stratigraphic tops (Appendices 1 and 2), seismic surveys (Appendix 3), water bores (Appendix 4), and gravity data (Figs 8 and 9).

Surface geology

The Giralia area is dominated by two asymmetric anticlines: the Giralia and the Marrilla Anticlines; these are flanked by three synclines (Condon et al., 1956). The main tectonism that generated this folding occurred during the Middle Miocene. To the west, the Giralia area is bounded by the Rough Range Fault, which is of critical relevance to the structural evolution of the region. To the east the stratigraphic sequence progressively onlaps over the Gascoyne Complex. The structural setting of the Giralia area is best illustrated as a pre-Cretaceous subcrop map (Fig. 2). This map was compiled from outcrop data (Condon, et al., 1956), and seismic structural maps of the top Korojon Calcarenite (Fig. 13), top Muderong Shale (Fig. 14), Early Neocomian unconformity (Fig. 15), top Callytharra Formation (Fig. 16), and the Golden West Hydrocarbons seismic map of the base Muderong Shale (Fig. 17).

The axes of the Giralia and Marrilla Anticlines (Fig. 2) are slightly converging, the axial trend of the first averaging 20° and that of the latter 30°. The Rough Range, Giralia, and Marrilla Anticlines show a clear plunge to the north, a steep eastern flank, and a bounding fault to the east. In general these are reverse faults (Figs 6, 7, 10, and 11), although the southernmost portion of the Rough Range Fault is normal in places (Figs 12, 13, and 14). Other minor anticlines are present to the south along the western flank of the Gascoyne Platform, and are informally called the 'Salt Marsh anticlines' (Fig. 18). These mostly trend north and are asymmetric, with the steeper flank generally to the east.

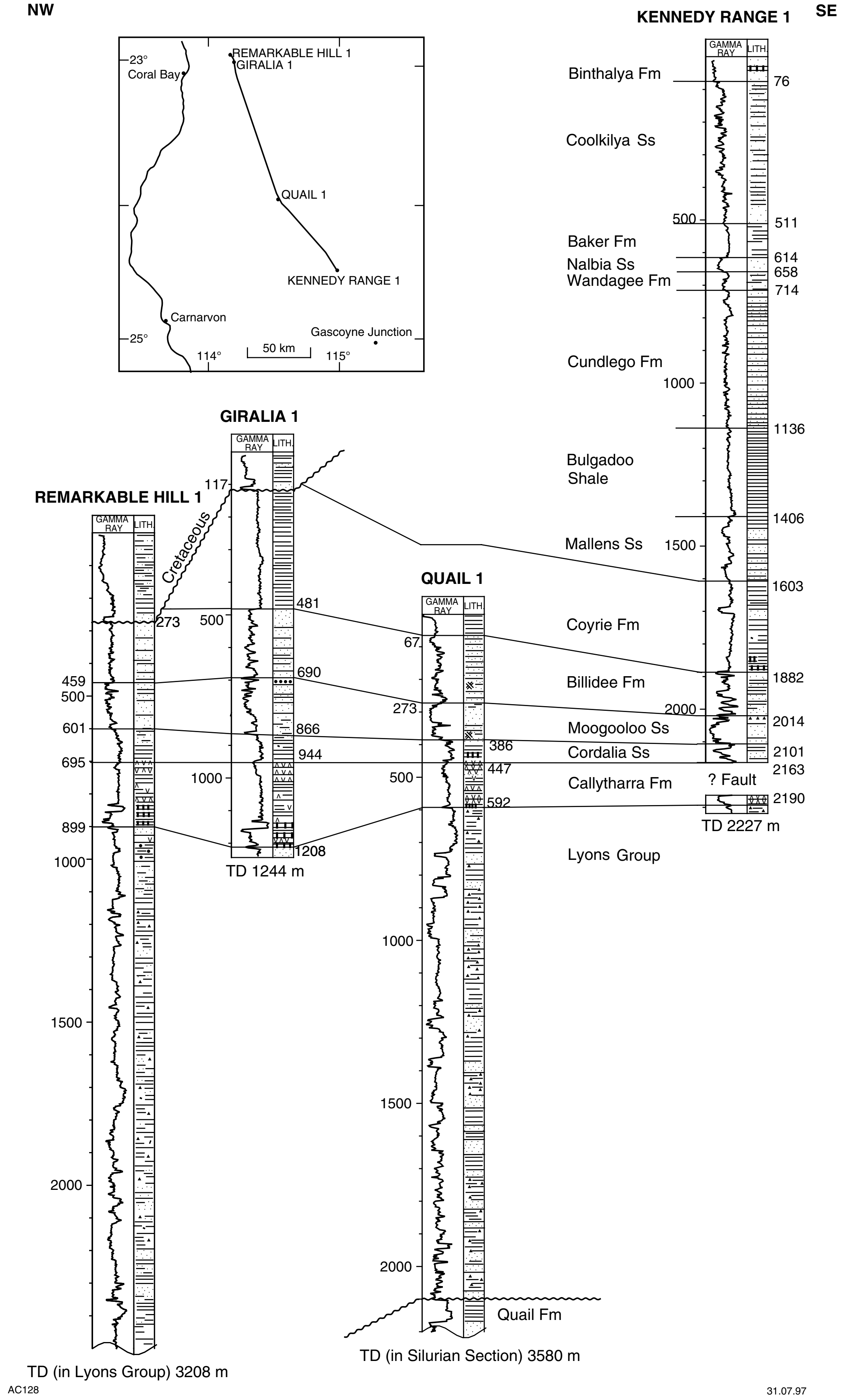


Figure 4. Permian correlation for the Merlinleigh Sub-basin and Giralia area

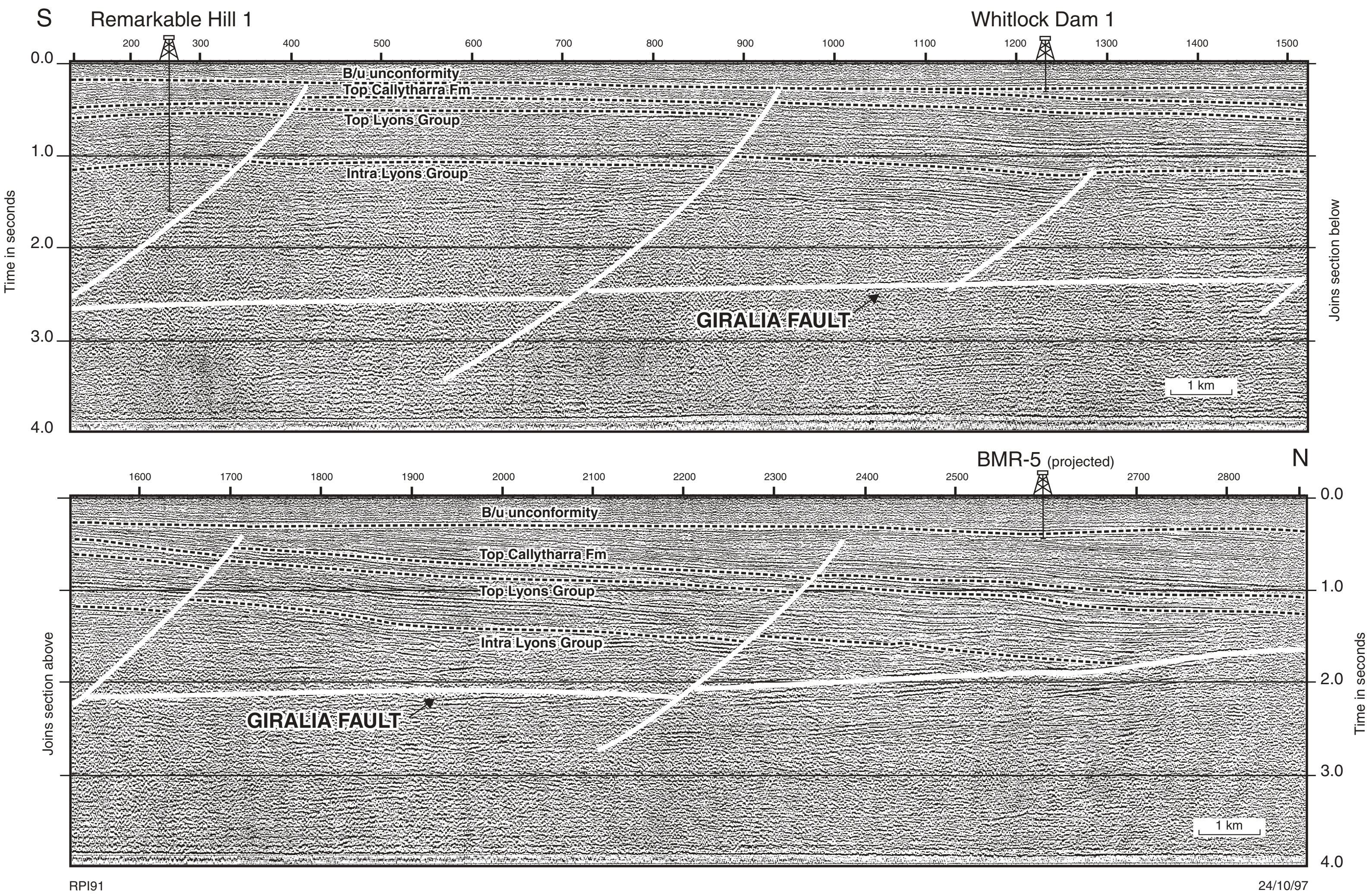


Figure 5. Seismic section 84-09, showing the structural setting of Remarkable Hill 1 and Whitlock Dam 1, the westward thickening of the Cretaceous–Tertiary section, and the contrasting attitude of the Palaeozoic strata. Line location shown on Figures 13 to 16. B/u unconformity = breakup unconformity in the Early Cretaceous

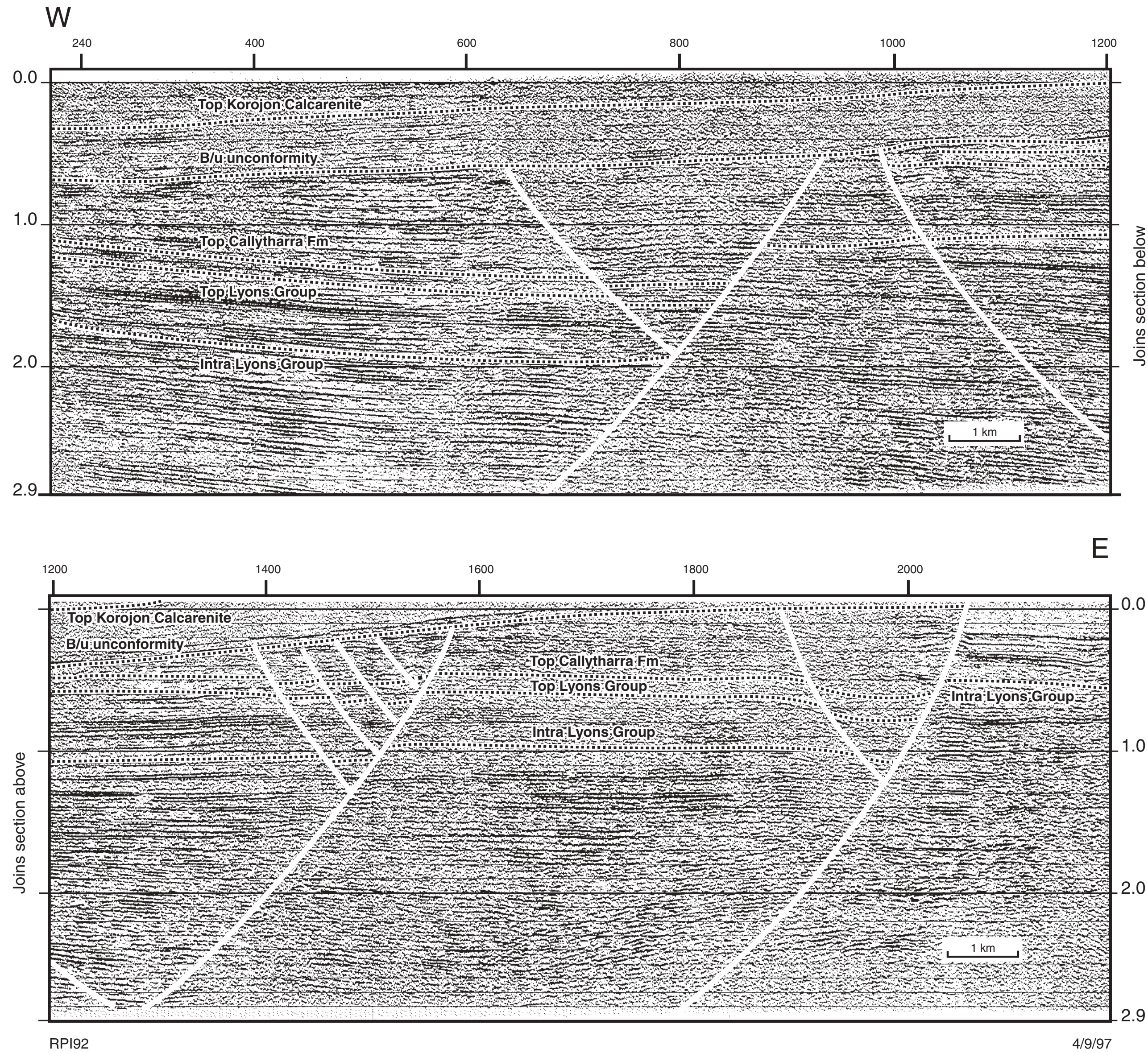


Figure 6. Seismic section 86-36, showing the crest of the Giralia Anticline. Line location shown on Figures 13 to 16. B/u unconformity = breakup unconformity in the Early Cretaceous

Seismic data

The tectonism that had the largest impact in the Giralia area can be constrained by the breakup of Australia from greater India. This is evident from seismic sections (Figs 5 to 7, 10 to 12), which indicate that the main tectonic movements occurred before the Main Unconformity, and from Rough Range data (Figs 3, 10, 11, and 12), which indicate that they occurred post-Jurassic. The style of the main faults suggests that the movements are related to strike-slip faulting resulting from wrenching at depth. The strike-slip component of the Rough Range Fault is suggested by the high angle of the fault, and the reverse vertical component of the fault becoming normal in the Bullara and Whaleback areas (Figs 13 and 14). The southern portions of the Marrilla, Giralia, and Rough Range Faults are irregular (Fig. 2) and broken into separate components showing differing trends (Condon et al., 1956, plate 5), and the Giralia and Marrilla Anticlines terminate abruptly with no or minimal southern plunge. Minor saddles are evident in the southern portion of the Giralia Anticline (Figs 14 and 15). Golden West Hydrocarbons suggested the presence of normal faults orthogonal to the main structure to explain these saddles (Fig. 17).

The top Callytharra Formation structural map (Fig. 16) suggests the presence of a major fault, separating the Giralia Anticline into a northern and southern component at about 22°50'S, 114°12'E. The different structural styles are also shown in Figure 6. This major fault corresponds to a lineament interpreted as a transfer fault on the gravity image (Fig. 9), here called the Toothawarra Transfer Fault. Low-amplitude folds and minor faulting of breakup age are also incorporated within

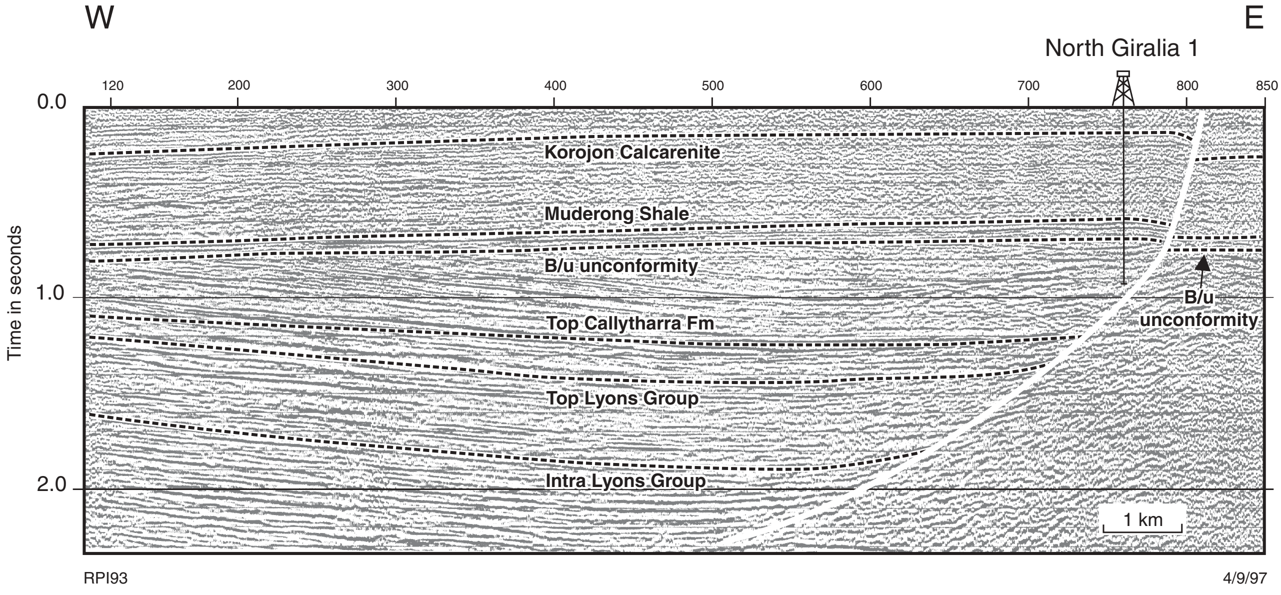


Figure 7. Seismic section 84-06, showing the structural setting of North Giralia 1. Line location shown on Figures 13 to 16. B/u unconformity = breakup unconformity in the Early Cretaceous

the Giralia Anticline. These folds and faults are likely to be related to secondary movements at an angle to the main strike-slip direction (Fig. 16). Seismic lines are almost entirely along dip and are sparse, making it difficult to interpret the direction of these minor faults.

Figure 5 shows that in the portion of the Giralia Anticline north of Whitlock Dam 1, progressively younger rocks subcrop against the main unconformity from south to north. This younging to the north suggests that the vertical throw of the fault controlling the anticline gradually increases northward. The sequence in Hope Island 1 indicates that sedimentary rocks, at least as young as Early Triassic, were deposited in the region. Figure 19, constructed from seismic and well data, shows that the boundary between the Mesozoic basins of the Northern Carnarvon Basin and the Palaeozoic Southern Carnarvon Basin is marked by a series of en echelon faults rather than a single fault line.

The axes of the Rough Range, Giralia, and Marrilla Anticlines are parallel to the direction of pre-existing rift faults controlling the Mesozoic downwarp. The Rough Range rift fault has been recognized since the drilling of Rough Range 1, whereas the Giralia and Marrilla rift faults are suggested by the regional geology (Fig. 2) and by the similarity of the three major faults in the area (Figs 6, 7, 10 to 12).

Seismic data indicate that the Callytharra Formation is truncated against the breakup unconformity between 27 to 31 km east of Sandalwood 1 (Fig. 16), whereas Bullara 1, Whaleback 1, and Sandalwood 1 intersect the unit east of the Rough Range Fault. A pre-Cretaceous subcropping, west-dipping normal fault (Fig. 6, western half of section) located between the Giralia and Rough Range Anticlines, is interpreted from seismic data (Fig. 16) to accommodate the different levels of the Callytharra Formation. This fault juxtaposes the Lyons Group and Callytharra Formation against the Byro Group below the Cretaceous sequence (Fig. 2). This interpretation provides a structural solution to accommodate the pre-Cretaceous strata encountered in the wells, even though the position of the fault is of low confidence because of poor-quality seismic data.

In 1962, WAPET recorded regional reflection and refraction seismic lines in the Warroora, Chargoo, and Gnaraloo areas (Fig. 18) near Lake Macleod (Hoelscher et al., 1962). Although the lines are widely spaced and of poor quality, the seismic data suggest a structural evolution similar to that of the area to the north. As in the north, Cretaceous–Tertiary reverse faults are superimposed on Palaeozoic normal faults downthrown to the west, suggesting an angular unconformity at the base Cretaceous level. The easterly dips of the Palaeozoic strata are interrupted by westerly dipping normal faults. The analogy with the better documented structural setting of the northern region suggests the regional presence of strike-slip faults with associated anticlines related to breakup in the Early Neocomian.

Gravity data

An explanation for the abrupt cessation to the south of the Giralia and Marrilla Anticlines at their highest structural elevation may be deduced from the images of the Bouguer gravity anomalies and their first vertical derivatives (Figs 8 and 9). Lineaments trending 315° are clearly recognized on the image (Fig. 9), despite the constraints of the limited database (Fig. 8). These lineaments are comparable to the transfer faults discussed by Malcolm et al. (1991) in the North West Cape area, where their orientation averages 290°. The transfer faults are interpreted to have occurred at breakup time but, as they cut Tertiary features such as

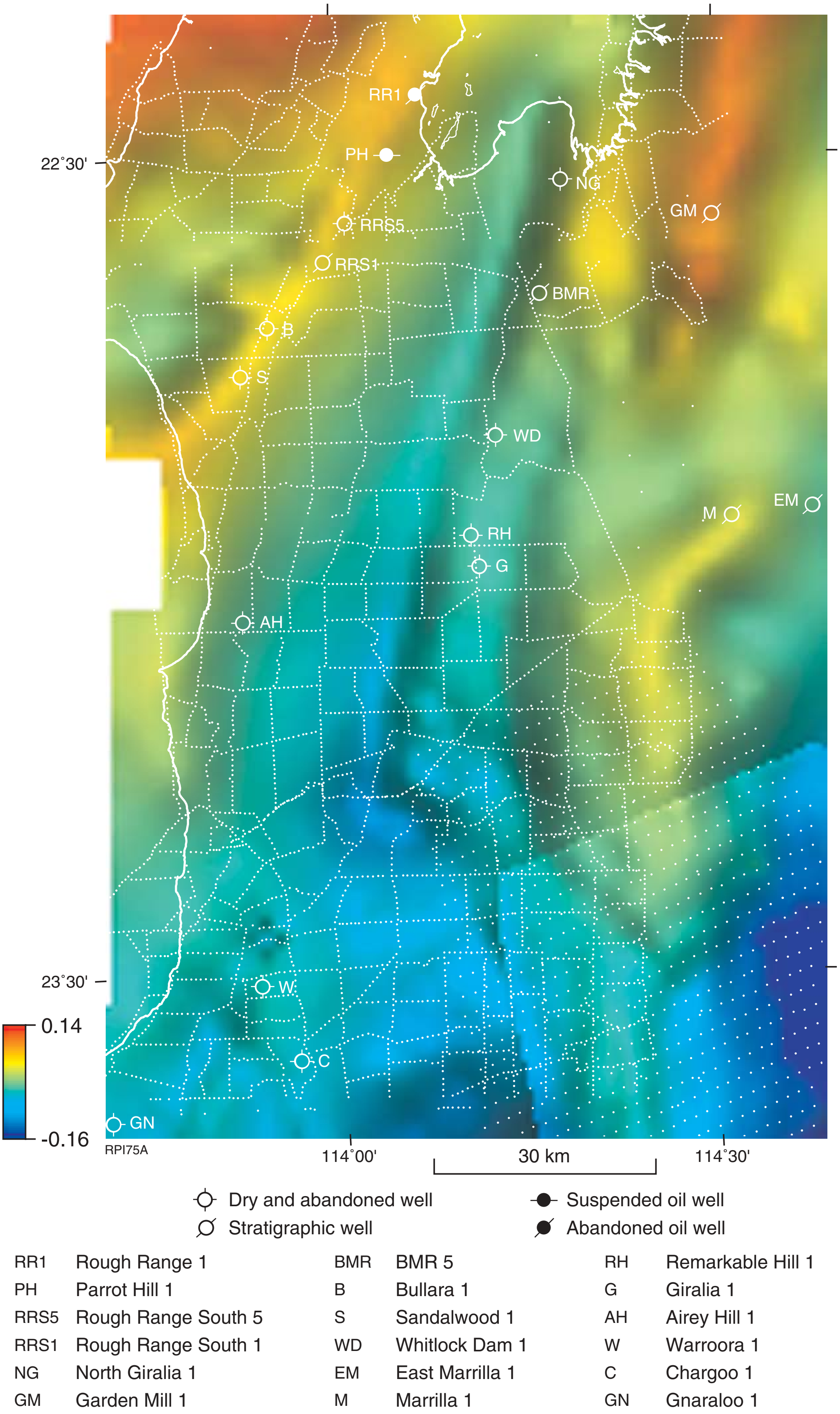
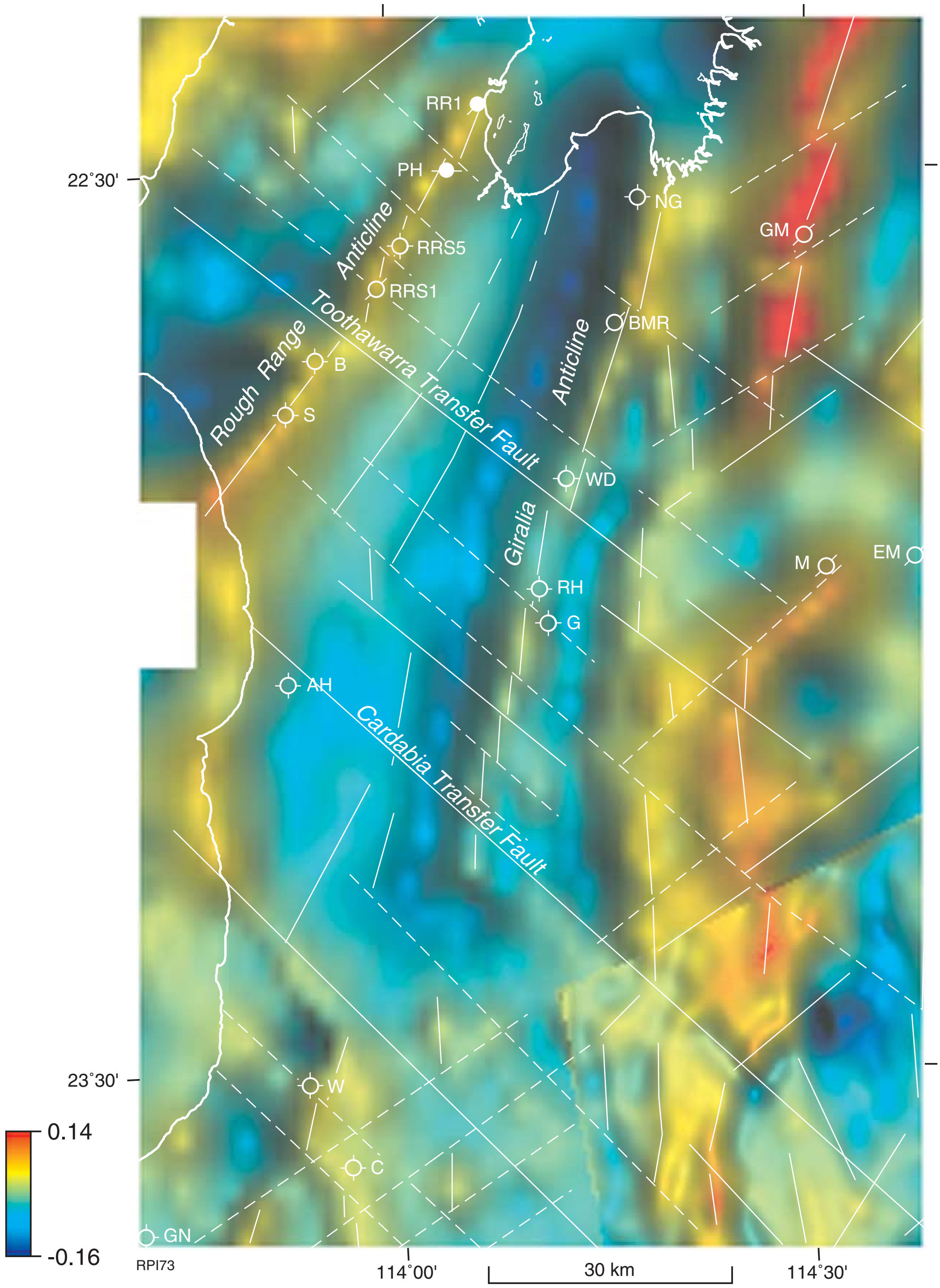


Figure 8. Bouguer gravity anomalies image of the Giralia area, created from Australian Geological Survey Organisation's database. Dots indicate gravity stations



Dry and abandoned well
Stratigraphic well
Suspended oil well
Abandoned oil well

RR1	Rough Range 1	BMR	BMR 5	RH	Remarkable Hill 1
PH	Parrot Hill 1	B	Bullara 1	G	Giralia 1
RRS5	Rough Range South 5	S	Sandalwood 1	AH	Airey Hill 1
RRS1	Rough Range South 1	WD	Whitlock Dam 1	W	Warroora 1
NG	North Giralia 1	EM	East Marrilla 1	C	Chargoo 1
GM	Garden Mill 1	M	Marrilla 1	GN	Gnaraloo 1

Figure 9. First vertical derivative image of Bouguer gravity anomalies with interpreted lineaments

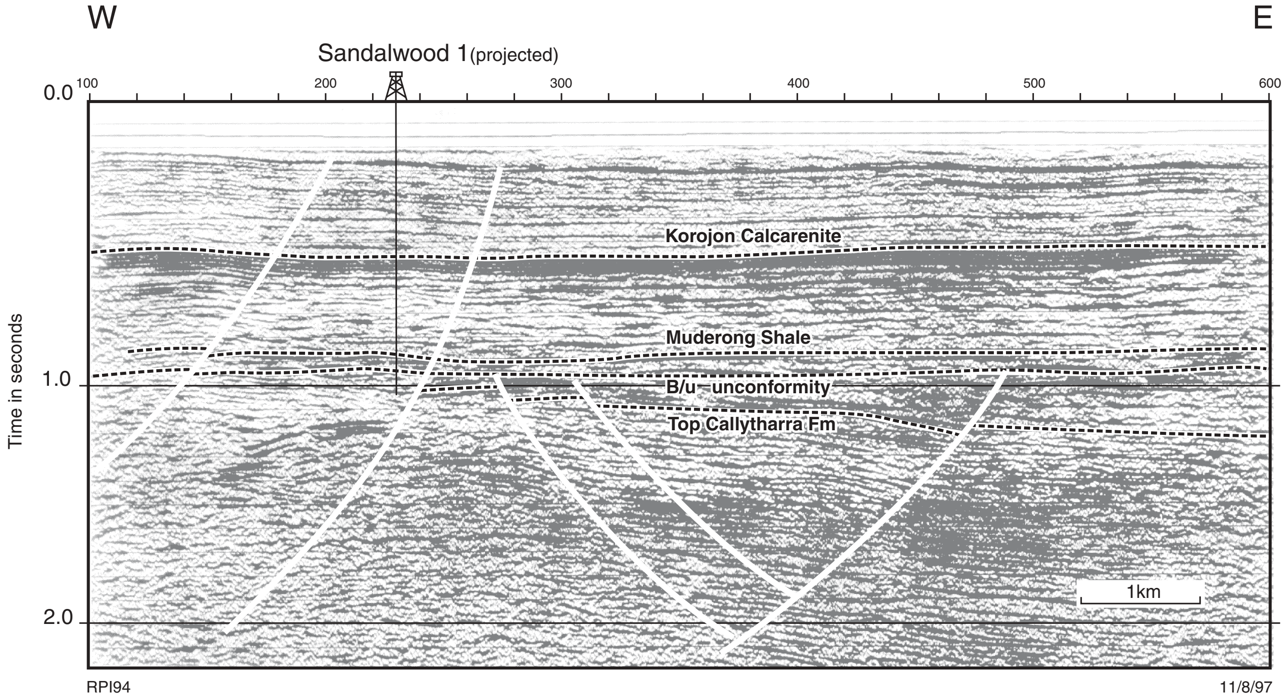


Figure 10. Seismic section SC89-10, showing the structural setting of Sandalwood 1. Line location shown on Figures 13 to 16. B/u unconformity = breakup unconformity in the Early Cretaceous

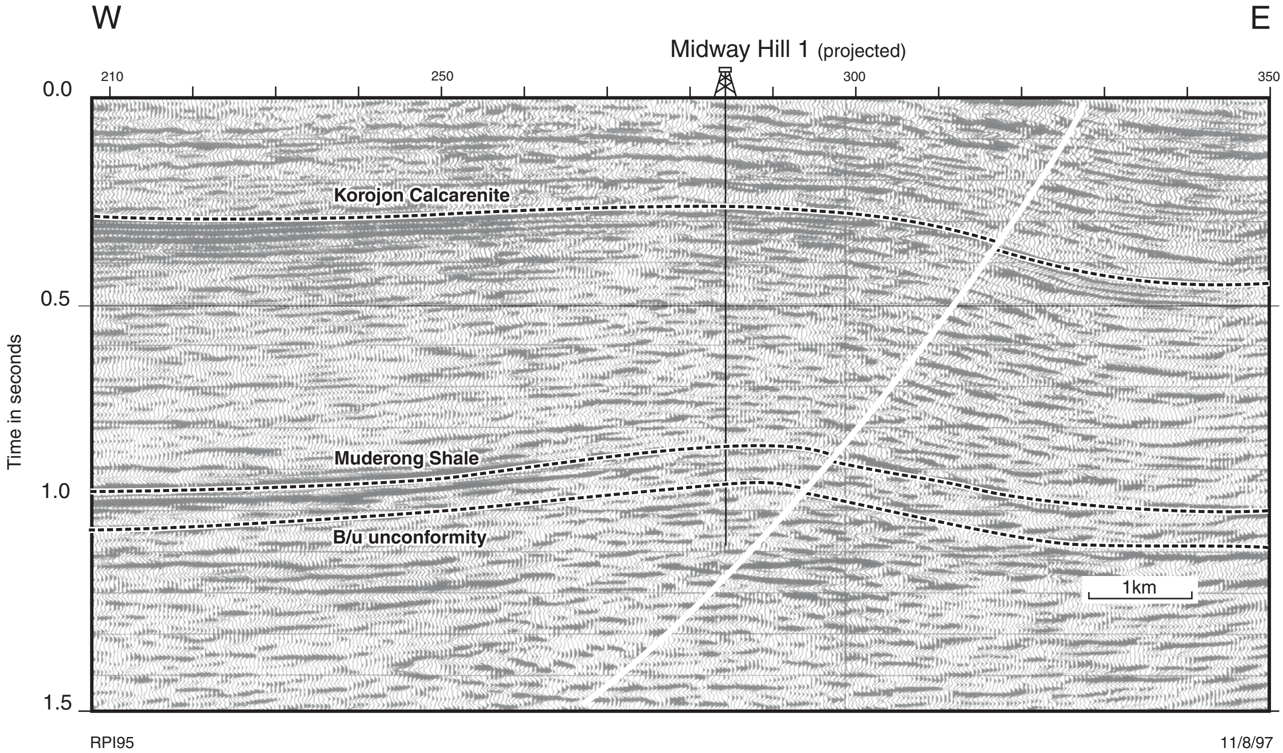


Figure 11. Seismic section A89-05, showing the structural setting at Midway Hill 1. Line location shown on Figures 13 to 16. B/u unconformity = breakup unconformity in the Early Cretaceous

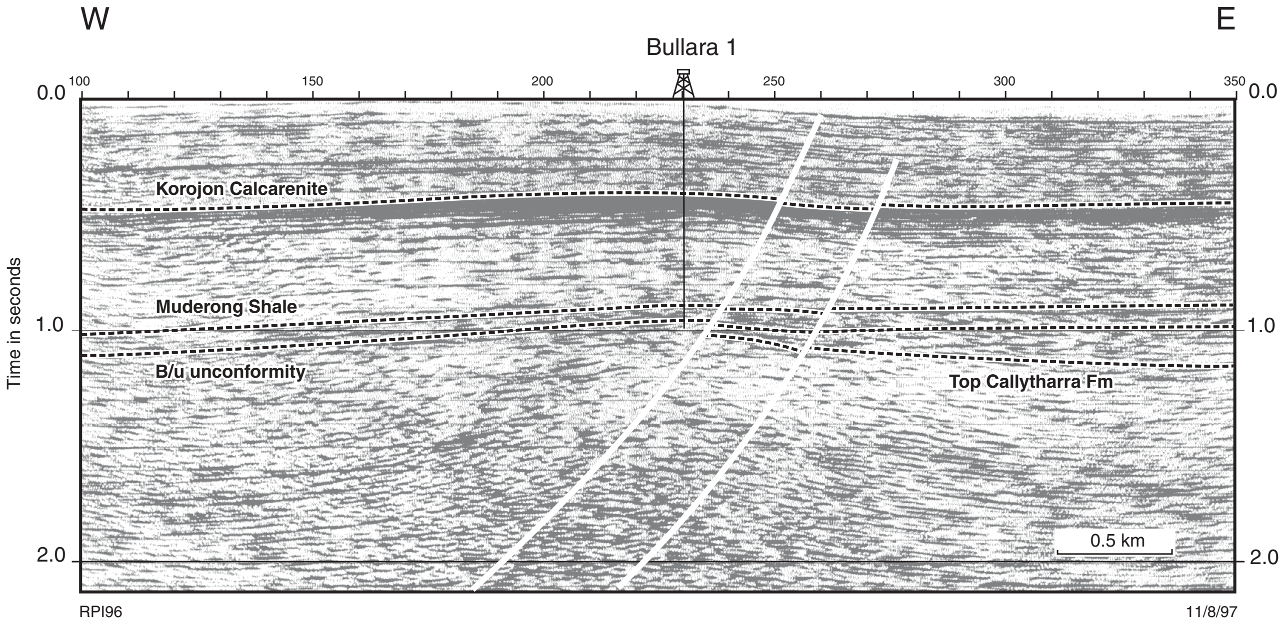


Figure 12. Seismic section A89-03, showing the structural setting at Bullara 1. Line location shown on Figures 13 to 16. B/u unconformity = breakup unconformity in the Early Cretaceous

the Giralia Anticline at 23°17'S, 114°10'E (Fig. 9), they appear to have been rejuvenated after the Middle Miocene. A similar structural evolution can be inferred from figure 4 of Malcolm et al. (1991).

Some of the northwest-trending transfer faults in the Giralia area indicate horizontal displacements of several kilometres. The most significant of these transfer faults, here named the Cardabia Transfer Fault, is responsible for shifting the axis of the Permian downwarp to the west and is probably responsible for the present shape of the coastline in the area (Fig. 2). This transfer fault is taken as the northern limit of the Gascoyne Platform.

Regional lineaments with four discrete directions (20–40°, 40–50°, 315°, and 360°) can be recognized on the gravity images (Figs 8 and 9). The north-trending lineaments are present in the eastern portion of the Giralia area (Fig. 9) and correspond to the strike of the Wandagee Fault (Fig. 2). These lineaments characterize the intersection between high-angle, westerly thrusting reverse faults at either the Main Unconformity or the post–Middle Miocene surface (Fig. 20, sections B–B' and C–C'). The en echelon pattern of the lineaments (Fig. 9) suggests that vertical faulting is associated with strike-slip movements.

The lineaments with 20–40° orientation in the central–western portion of the area (Fig. 9) correspond to the major Rough Range, Giralia, and Marrilla Anticlines. These anticlines are interpreted to have been generated at breakup and rejuvenated in the Middle Miocene. The lineaments with 40–50° orientation are only locally present in the Yanrey–Marrilla High, within the eastern portion of the Giralia area. These lineaments were probably related to the same movements that caused the 20–40° lineaments; the minor difference may be due to the more competent fabric of the basement rocks underlying the Yanrey–Marrilla High. As stated above, the 315° lineaments clearly identified in the southern part of the region (Fig. 9) are interpreted to indicate transfer faults of breakup age. The two prominent faults are the Toothawarra and Cardabia Transfer Faults (Fig. 2).

In the northern part of the area the north-northeasterly trending lineaments converge with the northerly trending lineaments, locally intersecting them. Towards the south the Salt Marsh anticlines (Fig. 18) are separated from the northerly trending lineaments of the Merlinleigh Sub-basin by an area where only transfer faults are evident (Fig. 2), possibly because of the limited data available.

Two other features are indicated by the Bouguer gravity image (Fig. 8): a gravity high a few kilometres south of South Rough Range 5, interpreted to correspond to a positive structure at basement and Palaeozoic levels; and a zone of thicker sedimentary sequence opening up in the southern part of the Giralia area at 23°30'S, 114°05'E. The presence of Silurian rocks in Quail 1 (Fig. 4) suggests that the downwarp lies at the northernmost end of the Silurian basin.

Basin development

Three discrete cycles, each terminating with a tectonic event are recognized in the Giralia area (Table 1). The lithostratigraphy intersected by the petroleum wells in the area is summarized in Appendix 2.

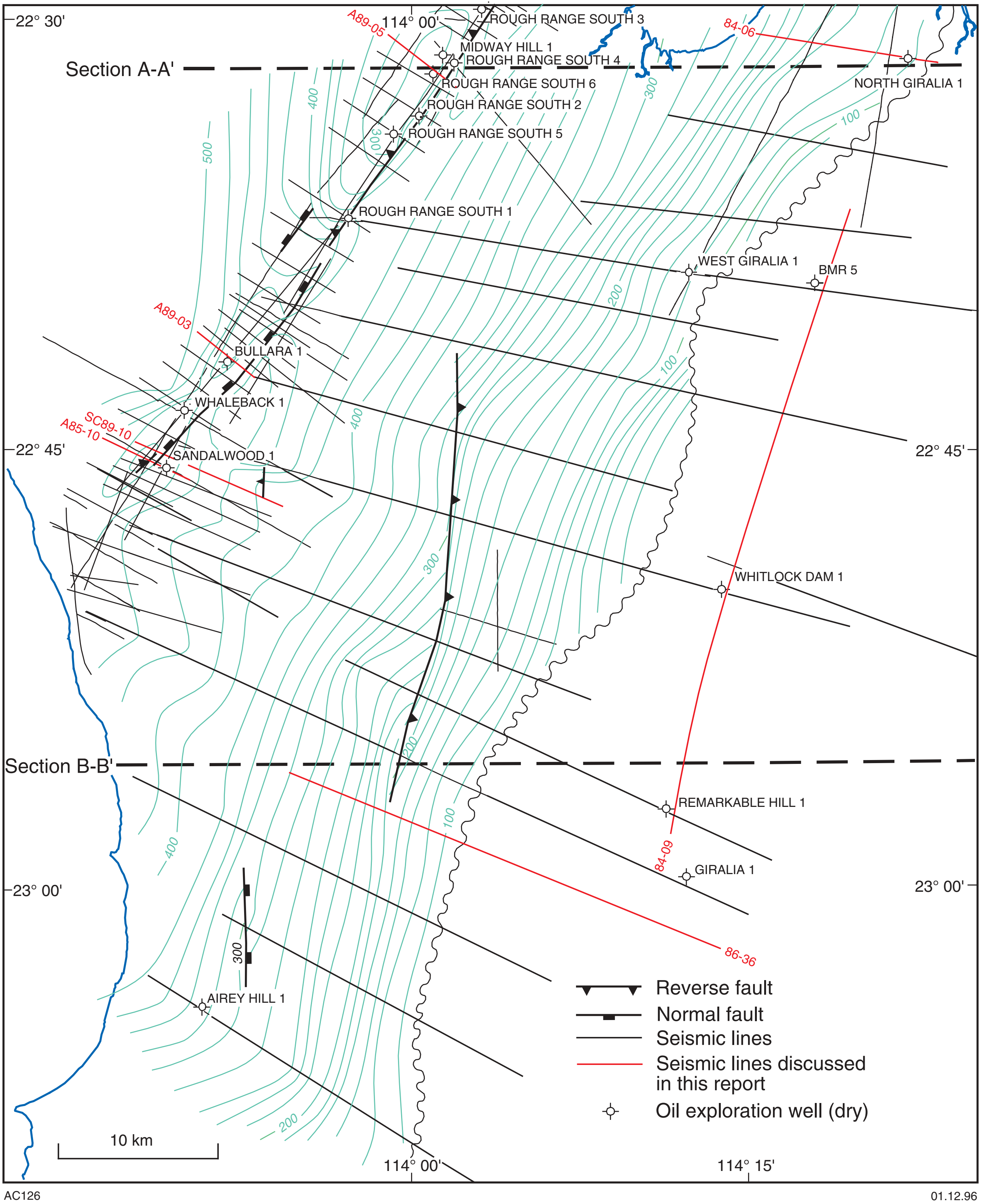


Figure 13. Seismic time contour map of top Korojon Calcarenite; contour interval = 20 ms, datum = sea level. Sections A–A′ and B–B′ are shown in Figure 20

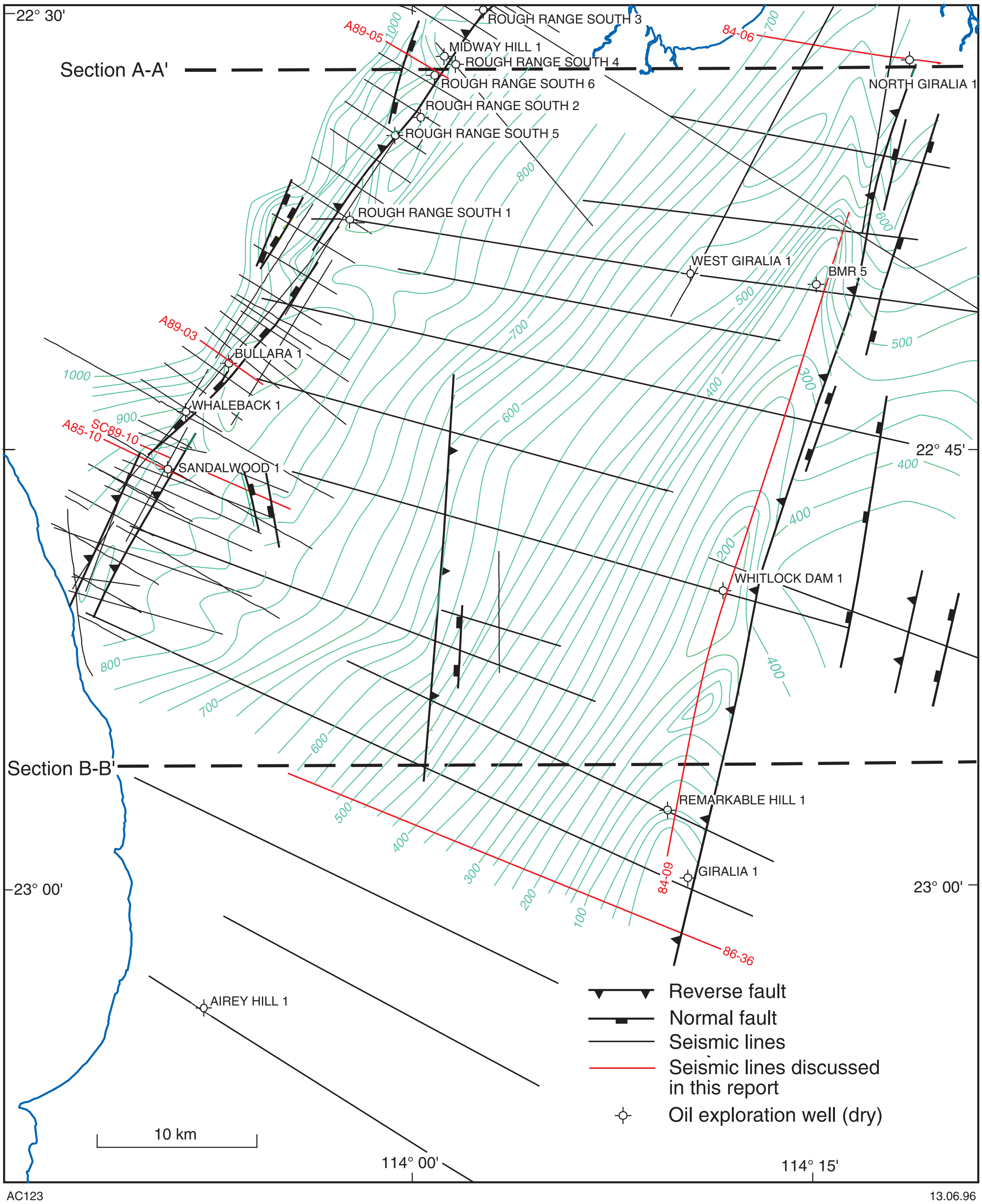


Figure 14. Seismic time contour map of top Muderong Shale; contour interval = 25 ms, datum = sea level. Sections A–A′ and B–B′ are shown in Figure 20

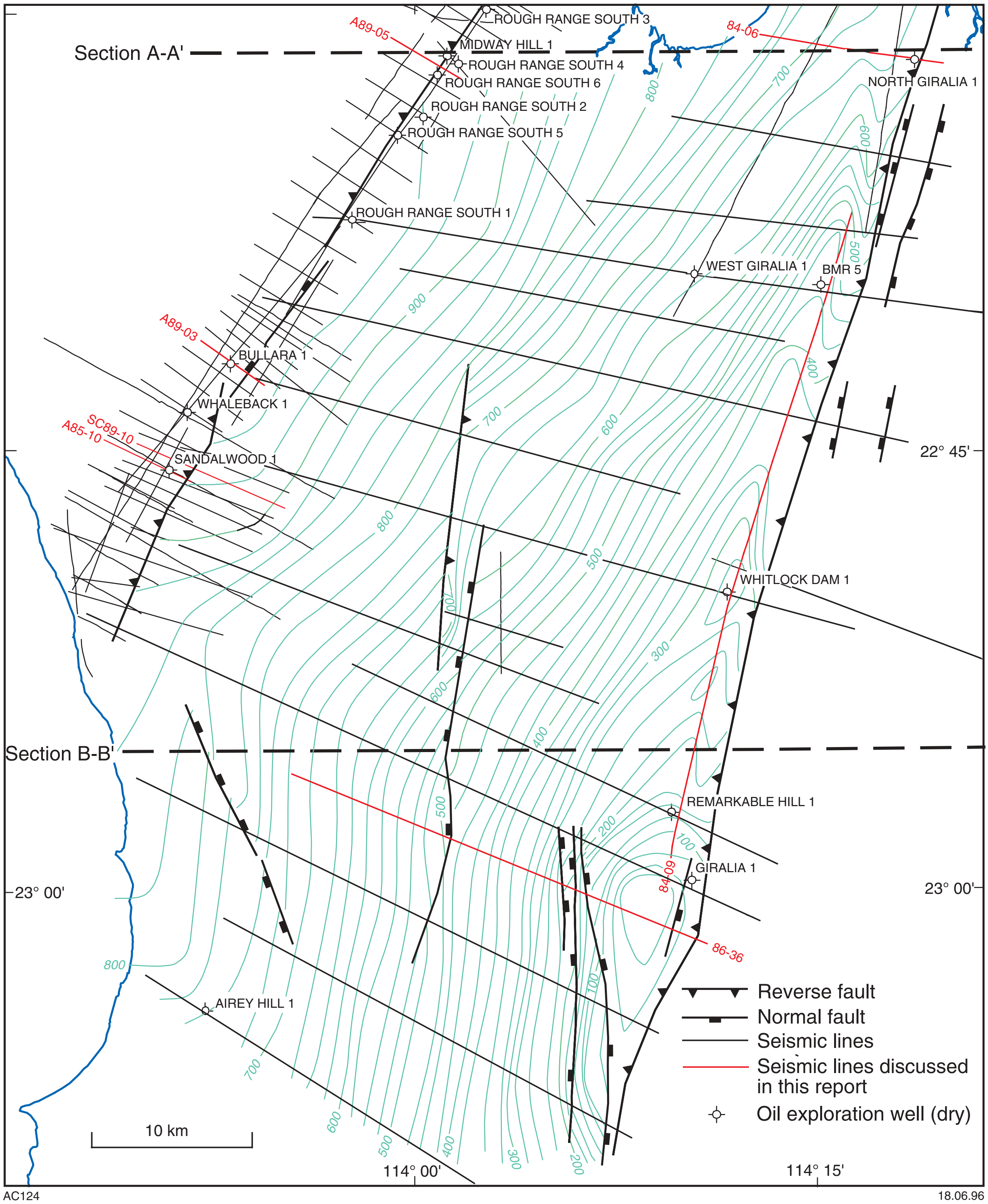


Figure 15. Seismic time contour map of Early Neocomian Unconformity; contour interval = 25 ms, datum = sea level. Sections A–A′ and B–B′ are shown in Figure 20

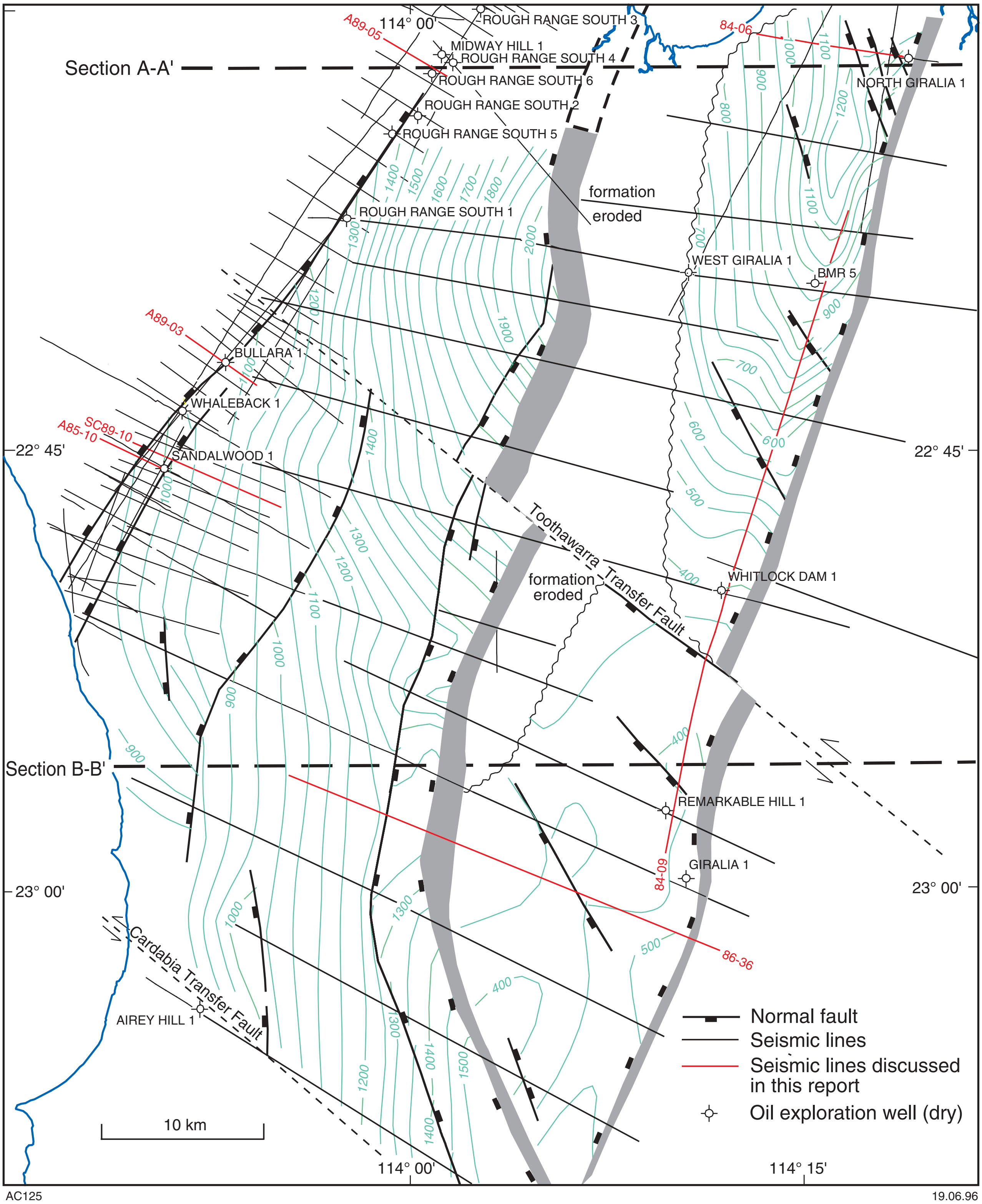


Figure 16. Seismic time contour map of top Callytharra Formation; contour interval = 50 ms, datum = sea level. Sections A–A′ and B–B′ are shown in Figure 20

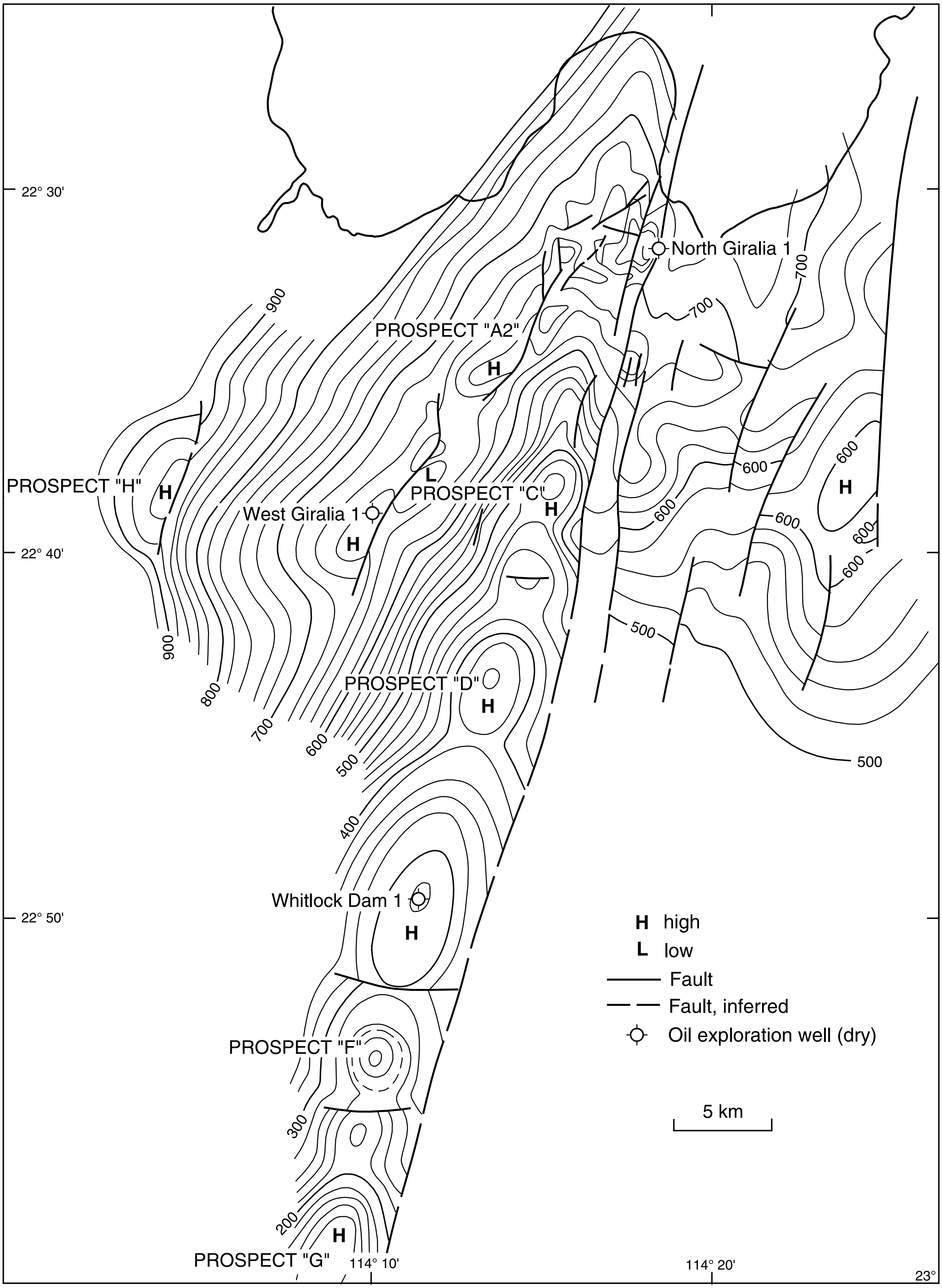


Figure 17. Seismic time contour map of base Muderong Shale along the Giralia Anticline (after Golden West Hydrocarbons Pty Ltd, 1985a)

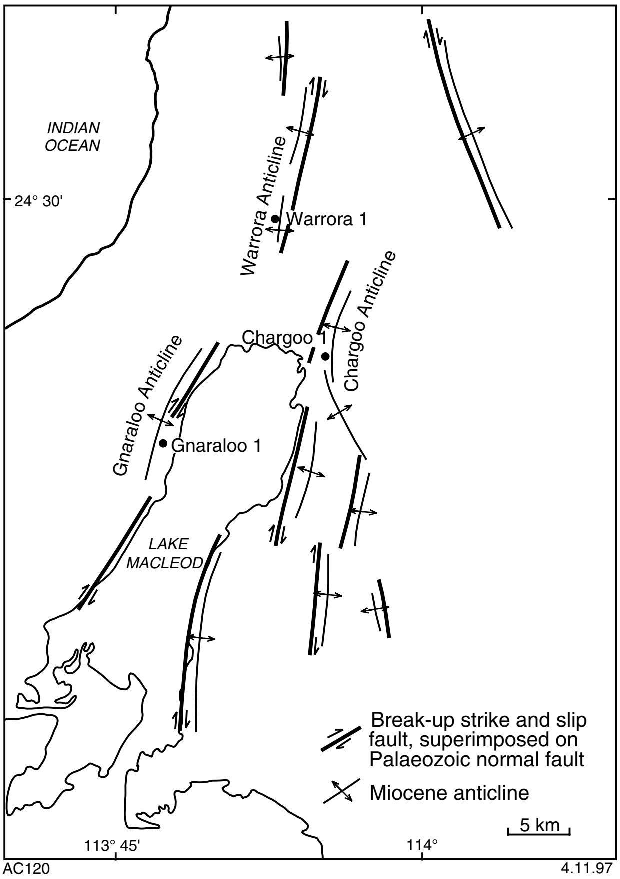


Figure 18. Salt Marsh anticlines (after Hocking et al., 1985)

Intracratonic cycle (Late Devonian – Early Carboniferous)

The oldest known Palaeozoic sedimentary rocks in the Giralia area are represented by Upper Devonian well-bedded fossiliferous limestone and fine-grained sandstone overlain by Lower Carboniferous limestone, with local terrigenous clastic beds (Sloanaker, 1955). These rocks were deposited within an extensive intracratonic sag basin, covering a large portion of the Southern Carnarvon Basin and extending offshore to the north. The basin was shallow with continuous subsidence, although the deposition of two episodes of shelf carbonates — namely the Gneudna Formation and the Moogooree Limestone — separated by fine-grained clastic rocks indicate some movement, probably epeirogenic in origin, in the hinterland. The glacigene rocks of the Upper Carboniferous Lyons Group suggest a sharp climatic change between the Early and Late Carboniferous. There is no clear evidence of tectonism at this time but a gentle epeirogenic upwarp is probable.

Rift valley cycle (Late Carboniferous – Early Triassic)

From the Late Carboniferous into the early part of

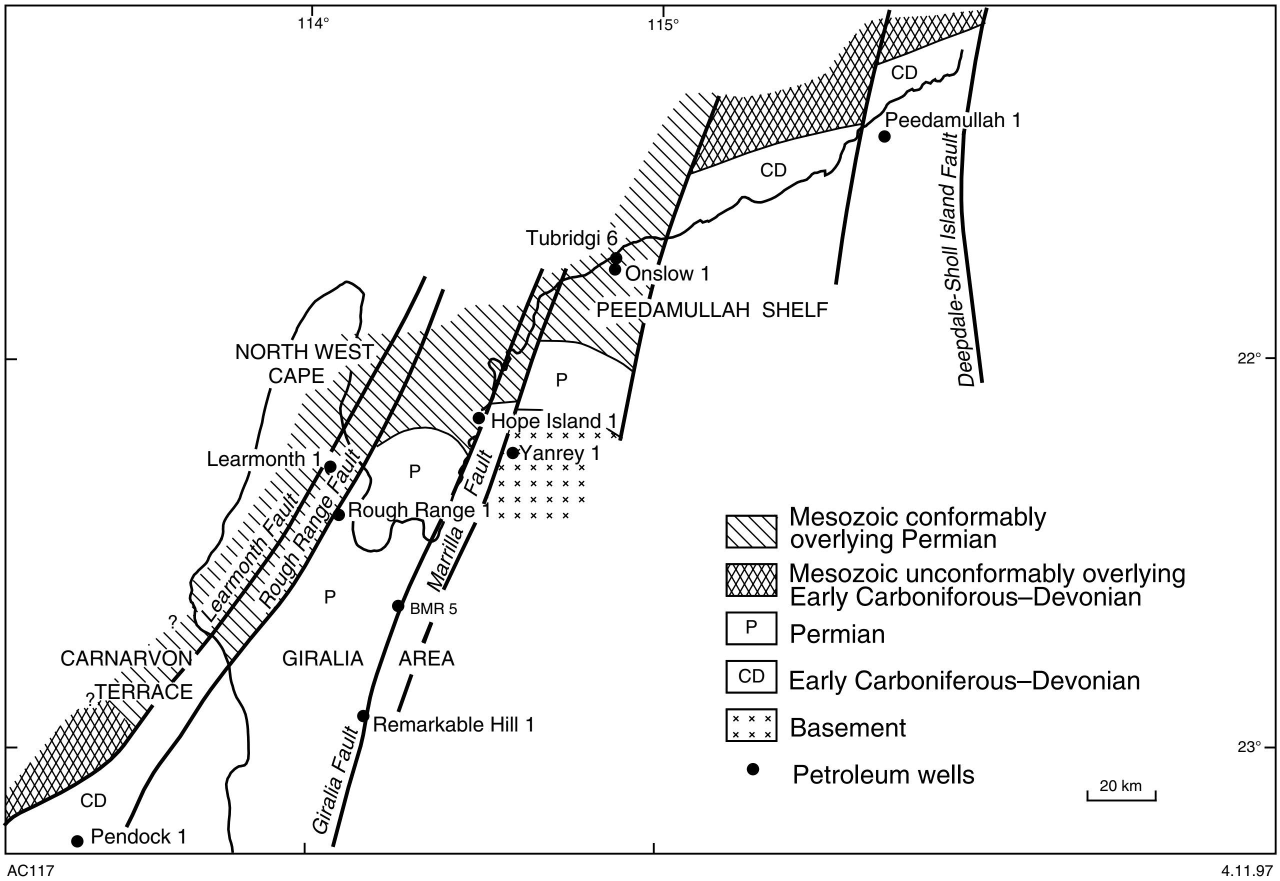


Figure 19. Southern limit of the Mesozoic sedimentation in the Giralia area and the Peedamullah Shelf

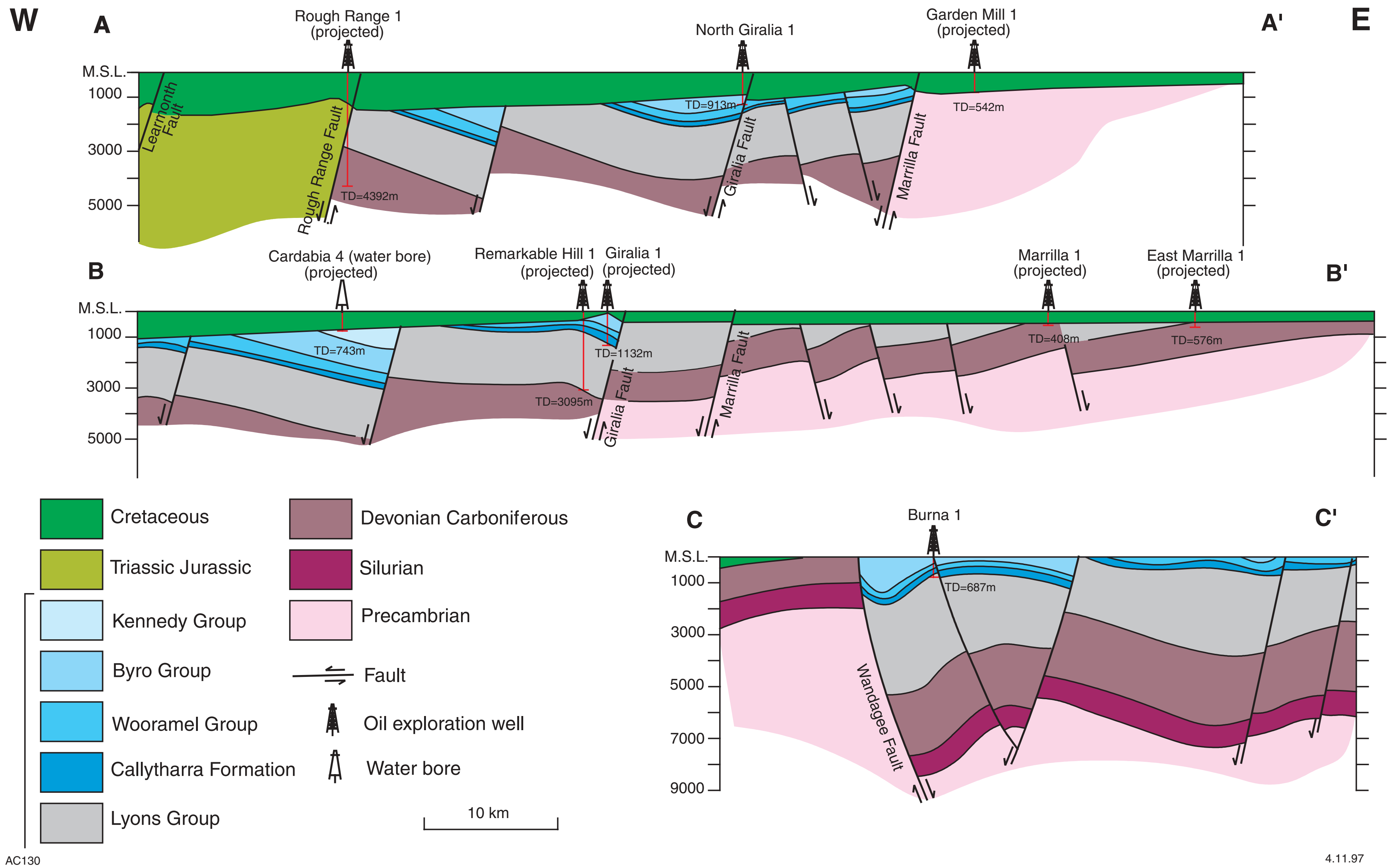


Figure 20. Structural cross sections across the northern Giralia area (A-A′), southern Giralia area (B-B′), and northern Merlinleigh Sub-basin (C-C′, modified from Iasky et al., in prep.). Datum is sea level, and wells total depths are from datum. Vertical exaggeration is 2. Location of cross sections shown on Figure 2

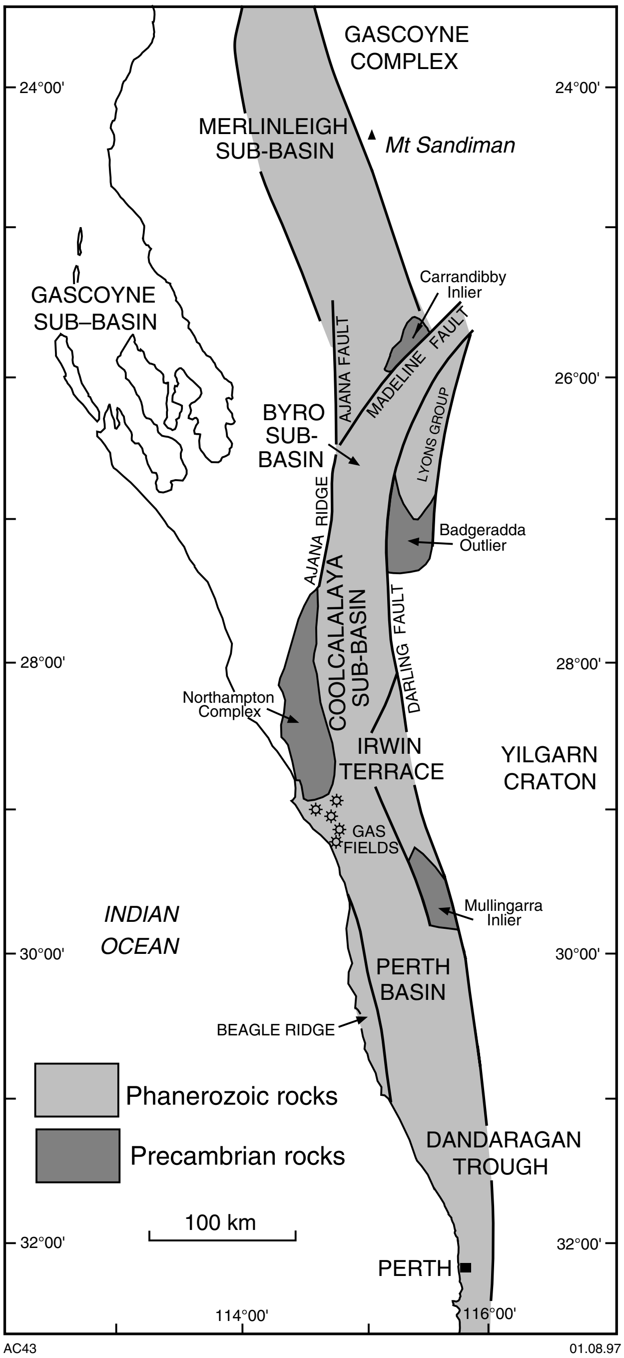


Figure 21. Distribution of Permian deposits within the Perth Basin, Coolcalalaya–Byro Sub-basin, and Merlinleigh Sub-basin

the Permian (Sakmarian) a fault-bounded rift valley developed. The rifting did not affect the Gascoyne Platform to the west and was synchronous with rifting in the Perth Basin. The rift valley contains a section of Upper Carboniferous – Permian sedimentary rocks that stretch northward from the Perth Basin and the Coolcalalaya–Byro Sub-basin to the Merlinleigh Sub-basin (Fig. 21). Shale, sandstone, siltstone, and minor amounts of lime-stone filled the rift valley, which failed to fully separate the continent and therefore may be regarded as an 'aborted rift' (Veevers, 1984). Sedimentation continued into the early Late Permian in the southeast portion of the Giralia area where the Kennedy Group filled the rift valley. In the northwest portion of the Giralia area, however, Lower Triassic rocks were deposited conformably on Upper Permian rocks. The entire rift valley phase was devoid of major tectonism, as indicated by the subparallel reflections on seismic data.

The Giralia area is here included within the Merlinleigh Sub-basin (Fig. 22), because the Upper Carboniferous – Permian Merlinleigh and Giralia rift valleys are connected (Fig. 2). The Gascoyne Platform therefore, is restricted to the area of mainly pre-Permian subcrop south of the Cardabia Transfer Fault. It is proposed here that the terms Yanrey Ridge and Marrilla High be replaced with the Yanrey–Marrilla High, because they cannot be separated on the gravity image (Fig. 9) and both represent the westernmost portion of the Gascoyne Complex (Fig. 22).

The Giralia area did not experience any significant structural deformation until the separation of Australia from India in the Early Neocomian, which generated widespread tectonic movements. Seismic data indicate that the main structures of the region formed at this time (Figs 5, 6, and 7). These structures are considered to be controlled by strike-slip movements with some associated vertical movements, both normal and reverse. Northwest-trending transfer faults were also generated at this time. Locally, substantial erosion followed before deposition of Cretaceous sediments.

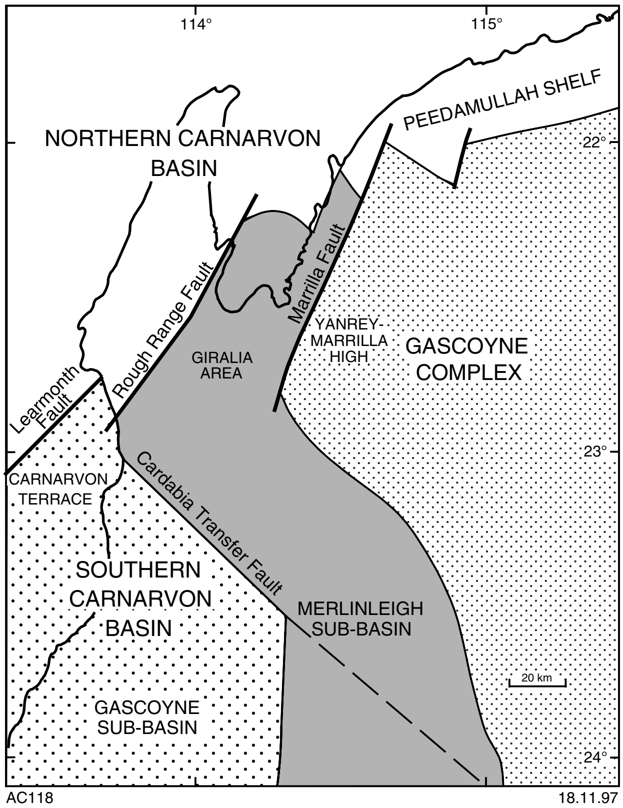


Figure 22. Proposed revision of boundaries for the Merlinleigh Sub-basin

Passive margin cycle (Cretaceous–Tertiary)

Breakup was followed by a major transgression and the deposition of Cretaceous and Tertiary rocks. Subparallel layers were deposited on a passive continental margin flanking the entire western edge of the Australian continent. Argillaceous marine deposition was followed by the deposition of shallow-water shelf carbonates in the Late Cretaceous – Tertiary. During the Middle Miocene, breakup faults such as the Rough Range and Giralia Faults were rejuvenated with relatively minor reverse movement. The Miocene faulting is interpreted to have a strong strike-slip component.

History of petroleum exploration

In 1947 Ampol Petroleum secured leases over all the onshore sedimentary basins along the northern and western coast of Western Australia. In the following years the Bureau of Mineral Resources (BMR) carried out regional geological and limited seismic surveys, focusing on the Giralia, Rough Range, and Cape Range Anticlines. Early seismic lines at Cape Range were mostly recorded along deeply incised valleys, which caused acquisition and processing problems that were difficult to resolve. Only in 1952 did petroleum exploration activities commence in earnest when WAPET was formed by a joint venture between Ampol and Chevron. Shell joined WAPET in the undertaking in 1957.

The 1953 Rough Range 1 oil discovery in the Lower Cretaceous Birdrong Sandstone triggered intense activity over the entire area, with both drilling (Appendix 1) and seismic (Appendix 3 and Fig. 23) campaigns taking place. The first two deep oil wells in the Giralia area, Warroora 1 and Giralia 1, were drilled by WAPET in 1955 on deeply eroded surface anticlines. In 1958 BMR drilled a stratigraphic test well, BMR 5, downplunge on the northern Giralia Anticline. In 1962 WAPET conducted a small seismic survey using analogue recording techniques in the southern part of the study area, and in the following year drilled Marrilla 1 as a stratigraphic well. East Marrilla 1 was the next well drilled by WAPET in 1963 aimed at testing the Birdrong Sandstone. Four years later, in 1967, WAPET tested two additional Salt Marsh anticlines with Chargoo 1 and Gnaraloo 1.

In 1968 Marathon Petroleum Australia recorded the Mia Mia seismic survey southeast of the Rough Range Anticline, and drilled Remarkable Hill 1 on the Giralia Anticline in a joint venture with WAPET. The well was designed to test the entire pre-Permian sequence, but was terminated in the Lyons Group. Remarkable Hill 1 was the last oil exploration well to be drilled in the area while it was held by WAPET. No drilling activity took place in the following decade.

Exploration recommenced in 1980 when a new permit was granted to a consortium headed by the Magnet Group's Meda Petroleum. Without additional seismic control, Airey Hill 1 was drilled in the same year. In 1982 Monarch Petroleum conducted a high-resolution seismic survey using a dynamite source, a near offset of 40 m, and a group interval of 40 m. From this survey shallow seismic horizons could be resolved to within 100 milliseconds (ms) of the surface, whereas previous seismic surveys could not resolve horizons above 400 ms. Operations were then taken over by Golden West Hydrocarbons who drilled Garden Mill 1 in 1983, West Giralia 1 and Whitlock Dam 1 in 1984–85, and North Giralia 1 in 1985.

Operatorship was transferred to S.R.L. Exploration in 1988. In 1990 the company drilled the most recent exploration well in the area, Sandalwood 1, on the boundary between the Giralia area and the Rough Range Anticline.

Analysis of results from oil exploration wells

The main results of oil exploration wells in the Giralia area are reviewed and discussed in terms of their original objectives and final results. These wells, together with other wells relevant to the area, are listed in Appendix 1, and the stratigraphic units intersected are summarized in Appendix 2. The results of Quail 1 and Burna 1 are discussed in Crostella (1995), while those of Lefroy Hill 1, Rough Range 1, Rough Range South 5, and Whaleback 1 are discussed in Crostella (1996a).

Giralia 1

Giralia 1 was drilled by WAPET in 1955 (Johnstone, 1955) primarily to test the Lower Cretaceous Birdrong Sandstone at the apex of the outcropping Giralia Anticline (Figs 14 and 20). The well encountered water-saturated Birdrong Sandstone at 104 m, but was continued to a total depth of 1244 m as a stratigraphic test to evaluate the petroleum possibilities of the underlying Permian clastic section. The surface structure was mapped on a regional scale by BMR, and in detail by WAPET near the well location. As stated in the well completion report, the Windalia Radiolarite outcrops in the core of the asymmetric anticline, which shows a gently dipping western flank. Conversely, dips range from 45° to 60° along the eastern flank, limited by a west-dipping fault subparallel to the axis of the structure. There are a number of minor culminations along the axis of the anticline (Figs 14 and 15). Giralia 1 was located at the apex of the southernmost, and most pronounced, of these minor culminations.

Johnstone (1955) states that south of the Cardabia 2 water bore (Fig. 2), the ridge on the eastern border of the Giralia Anticline breaks up into a series of irregularly spaced ridges, some of which have their axes at 45° to the main axial trend of the structure. Such a relationship could be indicative of strike-slip movements in the area.

Giralia 1 intersected the Lower Cretaceous Birdrong Sandstone at 104 m and the Main Unconformity at 118 m.

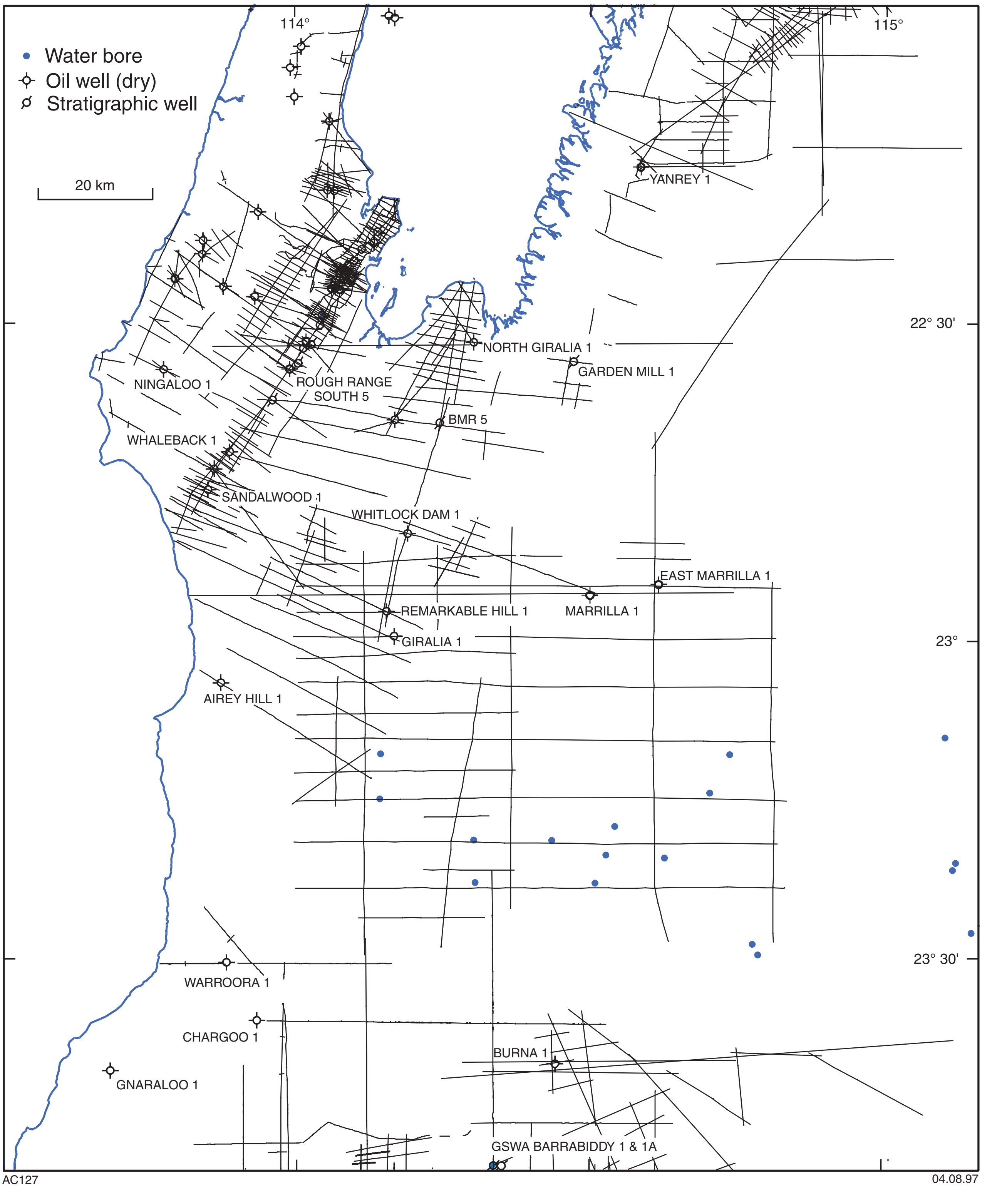


Figure 23. Regional seismic coverage in the Giralia area. 1:250 000 shot point base map is available at the Department of Minerals and Energy

Numerous cores were cut in the underlying Permian sequence allowing a detailed palynological study of the units penetrated (Mory and Backhouse, 1997). The well terminated in the Lyons Group (Appendix 2).

No shows of oil or gas were seen in the well, but inclusions of mature oil were detected in the Moogooloo Sandstone (Eadington, 1997). The salinity of the Birdrong Sandstone, Callytharra Formation, and Lyons Group was about 7000 ppm NaCl equivalent (NaCl equiv.) in the four samples analysed. Geochemical studies by GSWA indicate that the richest potential source rocks of the Permian succession, namely the shales of the Wooramel Group, are immature to marginally mature for oil generation at this location (Fig. 24).

WAPET considered that Giralia 1 was a valid test of the Birdrong Sandstone. However, it was felt that the test was not conclusive with respect to the Permian section because it was located downdip of the crest, as indicated by the unconformable relationship between Cretaceous and Permian rocks. A reinterpreted structural map of the area (Fig. 15) and cross section (Fig. 20, section B-B') support this interpretation. The structural map also indicates that at the top Birdrong Sandstone level there is an untested, structurally higher part of the anticline. This horizon is, however, above sea level and its seal can easily be breached because it is too shallow. The low salinity of water in the Birdrong Sandstone may also be caused by water flushing.

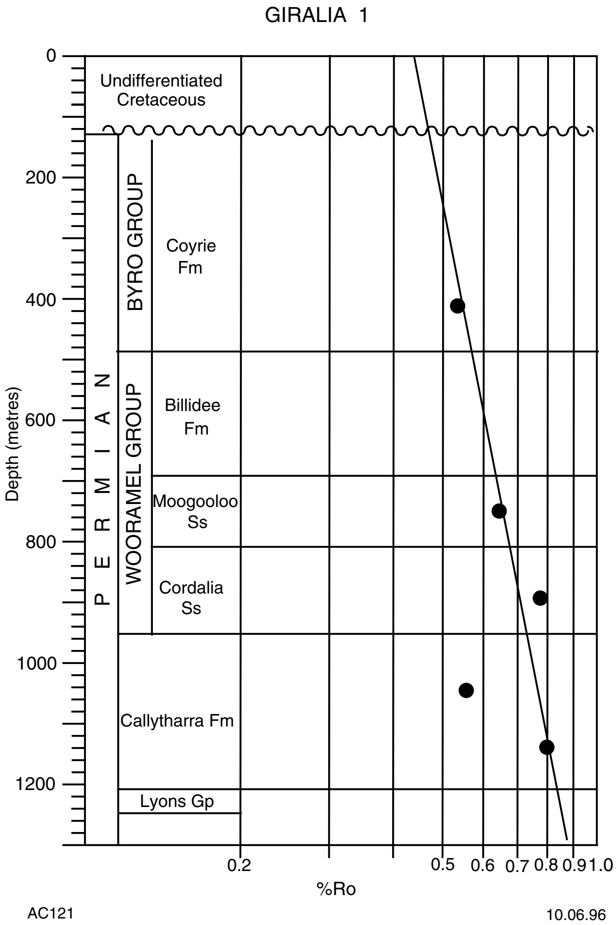


Figure 24. Depth versus vitrinite reflectance plot for Giralia 1, drawn from geochemical analyses by the Geological Survey of Western Australia

Warroora 1

Warroora 1 was drilled in 1955 by WAPET to a depth of 1827 m on the surface culmination of the Warroora Anticline (Johnstone and Pudovskis, 1955).

The Warroora Anticline is one of several anticlines exposed along the eastern and western shores of Lake Macleod (Fig. 18). These positive structures are slightly asymmetric, the eastern flank generally being steeper than the western one. The primary objective of Warroora 1 was the Birdrong Sandstone, below which the well was deepened without a definite target.

Warroora 1 penetrated a total of 343 m of Cretaceous rocks before entering the Lower Permian Lyons Group. The pre-Cretaceous section can be subdivided into interbedded siltstone, shale, and poorly sorted sandstone above 1510 m (Lyons Group), and thinly bedded fine-grained sandstone (possible Carboniferous) to the total depth of 1826 m. No signs of hydrocarbons were seen in cuttings, cores, or tests. However, while circulating and waiting for a test of the upper 4.6 m of the Birdrong Sandstone 'rainbows of oil' were observed in the mud. The mud recovered from the drillstem test (DST) no. 1 interval (331–335 m) showed the same 'rainbows' (Johnstone and Pudovskis, 1955). Salinity of the water recovered from the DST no. 2 interval (335–338.5 m) was 11 049 ppm NaCl equivalent.

WAPET considered Warroora 1 a valid structural test of the Birdrong Sandstone in the Warroora Anticline. However, the thin mostly calcareous sequence may not have provided an effective seal. If a reservoir and seal were present, the failure to find hydrocarbons may have been due to the lack of effective source rocks in the area where hydrocarbons may have been generated. Jurassic shales, considered to be the best source for hydrocarbons in the region, are expected to have been deposited more than 60 km to the west (Fig. 2), although the possible presence of Palaeozoic source rocks cannot be discounted. The WAPET 1962 seismic survey (Hoelscher et al., 1962) demonstrates that Warroora 1 is not an adequate Palaeozoic test because the well was not located on a Palaeozoic structure. Figure 25 illustrates the interpreted setting of the well.

BMR 5, Giralia

The stratigraphic well BMR 5 Giralia was drilled in 1958 on the northern plunge of the Giralia Anticline axis (Fig. 5; Bastian and Willmott, 1965).

The drillhole penetrated a typical Cretaceous succession to 479 m. At that depth, the basal Cretaceous Birdrong Sandstone unconformably overlies the Permian Byro Group. The well was continued to the total depth of 631 m.

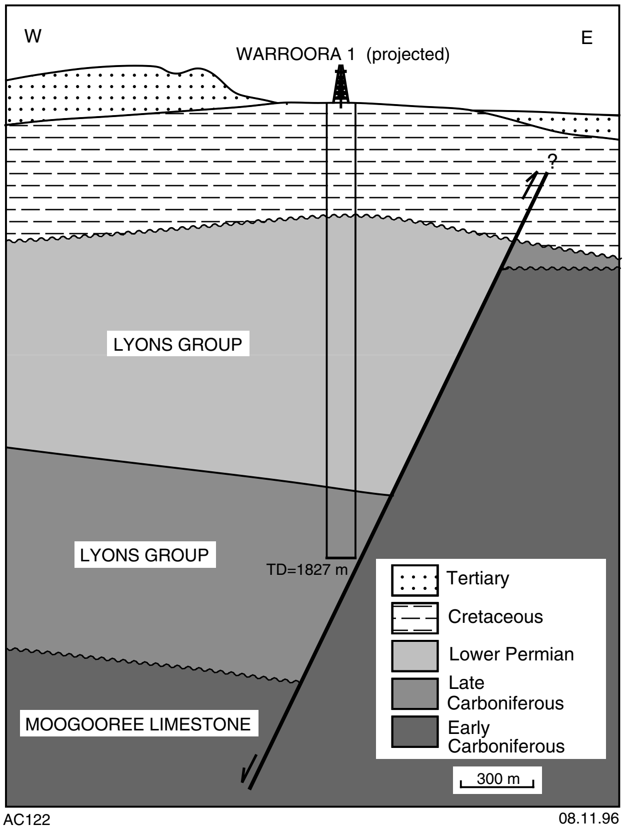


Figure 25. Section through Warroora 1, based on WAPET analogue seismic line 'Geradi-C' and surface geology

No occurrences of hydrocarbons were recorded. The weathered topmost few metres of the Permian section are interpreted as a Jurassic palaeosol horizon (Bastian and Willmott, 1965).

Figures 14 and 15 demonstrate that no trap is present at the BMR 5 location.

Marrilla 1

Marrilla 1 is a stratigraphic well drilled in 1963 by WAPET in the northern portion of the Giralia area to investigate the reservoir potential of the basal Cretaceous sequence. A secondary objective of the well was to determine the age and characteristics of the pre-Cretaceous rocks (Johnstone et al., 1963).

Marrilla 1 was drilled to a total depth of 457 m in the centre of a magnetic anomaly located by BMR. Below alluvium the well penetrated a typical Cretaceous sequence (Appendix 2) to 411 m. The glauconitic, fine- to coarse-grained Birdrong Sandstone unconformably overlies limestone that Johnstone et al. (1963) tentatively referred to as Silurian. No evidence of this Silurian age was offered, and the rocks can be equally interpreted as Devonian or Early Carboniferous based on lithological correlation. On regional grounds the latter age is preferred. The interpreted structural position of Marrilla 1 is shown on Figure 20.

The Birdrong Sandstone contains water of about 5000 ppm NaCl equiv. salinity; no aquifers are present in the pre-Cretaceous sequence.

East Marrilla 1

East Marrilla 1 was drilled by WAPET in 1972 to a total depth of 639 m to evaluate the hydrocarbon potential of an interpreted cross-basin high present in pre-Permian rocks, in the northern portion of the onshore Carnarvon Basin. The east–west high was expected to separate the Merlinleigh Trough from the Ashburton Trough. The East Marrilla prospect was described as a north–south anticline with four-way dip closure (Osborne, 1972).

From 30.5 m, below undifferentiated Quaternary and possibly Tertiary rocks, the well encountered a Cretaceous succession down to 375 m, where the Birdrong Sandstone unconformably overlies Upper Carboniferous claystones of the Lyons Group (Appendix 2). The well was terminated at 639 m in the Lower Carboniferous Moogooree Limestone and no hydrocarbon shows were encountered. In this well the Birdrong Sandstone has the usual regionally widespread good reservoir characteristics, with sonic-derived porosity values ranging from 25 to 30%. The unit was, however, 100% water-saturated and a water salinity of 14 000 ppm NaCl equiv. was calculated. Neither source nor reservoir potential could be demonstrated from the Moogooree Limestone (Osborne, 1972).

The stratigraphic sequences in Marrilla 1 and East Marrilla 1 indicate that the fault to the east of Marrilla 1 is downthrown toward the basin (i.e. to the east) throughout the Permian, and that it was reactivated during a later phase of tectonism in the Early Neocomian or Middle Miocene. Presently East Marrilla 1 is structurally higher than Marrilla 1. The enclosures attached to the East Marrilla 1 well completion report indicate that the fault rebounded as a high-angle reverse fault overthrown to the west, suggesting strike-slip movements. The structural position of East Marrilla 1 within the region, as interpreted by the GSWA, is shown in Figure 20.

The postulated four-way dip closure cannot be confirmed and the validity of the test is questionable. Furthermore, East Marrilla 1 is located a considerable distance from the known Jurassic source rocks deposited within the North West Cape.

Chargoo 1

Chargoo 1 was drilled in 1967 by WAPET in order to test the basal Cretaceous Birdrong Sandstone in the Chargoo Anticline (Smith, 1967), one of the Salt Marsh positive features surrounding Lake Macleod (Fig. 18). The Chargoo structure is a north-trending, sinuous, asymmetric anticline with the western flank slightly steeper than the eastern one. This structural attitude is against the regional setting but consistent with a strike-slip setting. A secondary objective of the well was to identify the pre-Cretaceous succession. A specific location could not be identified from the 1962 WAPET seismic survey and it is possible that the well was located on the downthrown side of a Palaeozoic fault.

Chargoo 1 was spudded in the Upper Cretaceous Toolonga Calcilutite and continued through the typical Cretaceous succession of the Carnarvon Basin into the basal Cretaceous Birdrong Sandstone at 384 m. Drillstem tests over the Birdrong Sandstone yielded water with a salinity of 7400 ppm NaCl equivalent. At 409 m the Birdrong Sandstone unconformably overlies the Lower Permian Lyons Group. The well was terminated at 428 m in the Lyons Group. No indications of hydrocarbons were found (Smith, 1967).

The failure of Chargoo 1 to intercept hydrocarbons in the Birdrong Sandstone appears to be related to the considerable distance of the well from any effective (Jurassic) source rocks and to poor retention potential.

Gnaraloo 1

Gnaraloo 1 was drilled by WAPET in 1967 to test the hydrocarbon potential of the Birdrong Sandstone in the Gnaraloo Anticline (Smith, 1967), one of the Salt Marsh structures (Fig. 18). The Gnaraloo structure is a sinuous slightly asymmetric anticline with the eastern flank steeper than the western one, consistent with the regional structural setting. Identification of pre-Cretaceous rocks was a secondary objective. The seismic survey conducted by WAPET in 1962 (Hoelscher et al., 1962) did not assist the company to position the well because of its limited coverage.

The well was spudded in the Miocene Trealla Limestone and continued through the Tertiary and Cretaceous sequence into the Birdrong Sandstone (the primary objective) at 410 m (Appendix 2). The formation water recovered with a DST had a salinity of 7300 ppm NaCl equivalent. ‘Rainbows of oil’ were seen at the conclusion of the test. At 450 m the Birdrong Sandstone unconformably overlies the Carboniferous Quail Formation. The well was terminated at 502 m within that unit. Although minor gas shows were recorded from the Quail Formation, no meaningful indications of hydrocarbons were encountered in the well.

The significance of the reported ‘rainbows of oil’ cannot be assessed. It is interpreted that Gnaraloo 1 failed to intercept hydrocarbons in the Birdrong Sandstone probably because it is located too far from the Mesozoic shales, which are the proven effective source rocks of the Carnarvon Basin. However, Palaeozoic source rocks may have generated hydrocarbons that could migrate upward into the Birdrong Sandstone via fault planes or from subcropping Palaeozoic strata. In this case, a weak seal may be the reason for the absence of hydrocarbons.

Hope Island 1

Hope Island 1 was a stratigraphic test drilled by WAPET during 1968 on the northwestern corner of Hope Island, on the eastern side of the Exmouth Gulf (Bowering, 1968). The well was part of the WAPET island drilling program and was not drilled on any known structure. It was located on the western side of the Giralia Fault (Fig. 2), previously termed by WAPET as the West Yanrey Fault. The western side of the fault was downthrown during Permian and older times, but is presently upthrown. This regionally widespread rebound has been described in the section dealing with the structure of the area.

Below 208 m of Quaternary cover, Hope Island 1 penetrated a Tertiary and Cretaceous section to a depth of 890 m (Appendix 2). From 890 to 912 m the Birdrong Sandstone was penetrated, and a DST across the interval produced brackish water. At 912 m the well entered shale and sandstone of the Triassic Locker Shale. From 1029 to 1427 m (total depth) Hope Island 1 penetrated sandstone, richly fossiliferous limestone, and siltstone of the Permian Kennedy Group (Bowering, 1968).

The Kennedy Group in Hope Island 1 is lithologically distinct from outcrops in the Kennedy Range and appears to be more marine in origin. This difference prompted the introduction in the literature of the name Chinty Formation (Hocking, 1985; Hocking et al., 1987). The nominated type section is in Onslow 1 (2096–2258 m) between the Locker Shale and strata then assigned to the Byro Group. The usage of Chinty Formation virtually replaced the previous term, the Kennedy Group, in the general Giralia – Peedamullah Shelf area. Consequently, the Kennedy Group was used in the Merlinleigh Sub-basin and the Chinty Formation in the Giralia – Peedamullah Shelf area, with an uncertain relationship between the two units. A GSWA study that includes the Permian section in Onslow 1 discusses the lithostratigraphic units of the Kennedy Group in detail (Mory and Backhouse, 1997). The study demonstrates that in Hope Island 1 the section below the type Chinty Formation, from 2258 m to about 2496 m, can be correlated with the Kennedy Group units outcropping in the Kennedy Range. Consequently, Mory and Backhouse (1997) assigned the interval 2096–2496 m in Onslow 1 to the Kennedy Group; the Chinty Formation is present from 2096 to 2258 m, but no formations were differentiated below it.

No shows of hydrocarbons were observed in Hope Island 1. Dips average 3–7° throughout the well without a predominant azimuth direction. The Lower Cretaceous Birdrong Sandstone and the sandstone present within the Triassic Locker Shale and the Permian Kennedy Group have good reservoir characteristics.

The most significant information obtained from Hope Island 1 is that there is a continuous sequence of Permian and Lower Triassic sediments present in the area.

Remarkable Hill 1

Remarkable Hill 1 was drilled by Marathon Petroleum Australia in 1968–69 to evaluate the petroleum potential of the Palaeozoic sequence in the area. The well was drilled on a subsurface seismically defined anticlinal feature. At the Lower Permian level the anomaly was interpreted to have an areal and vertical closure of 65 km^2 and 122 m, respectively (Berven, 1969). The structure was of sufficient magnitude that a discovery could have led to development of commercial reservoirs. The Birdrong Sandstone was not considered an objective because it was already unsuccessfully tested locally in the structurally higher Giralia 1. Carboniferous, Devonian, Silurian, and Ordovician rocks were the primary objectives of Remarkable Hill 1.

The well was spudded in the Gearle Siltstone and drilled through 273 m of Cretaceous rocks (Appendix 2). The Cretaceous rocks unconformably overlie rocks of Permian age identified as the Wooramel Group, Callytharra Formation, and Lyons Group. The well was terminated at 3206 m in a sequence referred to as undifferentiated Carboniferous by Berven (1969). However, it is here considered part of the Lyons Group because of the presence of pebbles and erratics of granite, chert, quartzite, and limestone within a siltstone–sandstone sequence.

No shows of oil or gas were encountered during drilling, but inclusions of oil with a low level of maturity were detected within the Moogooloo Sandstone (Eadington, 1997). An unconformity was inferred from seismic data by Marathon Petroleum at about 3850 m. This unconformity should represent the contact between the Lower and Upper Carboniferous. In general, dips appear to be less than 5°. Geochemical studies by GSWA indicate that in the well the Wooramel Group is immature for oil generation since the vitrinite reflectance value is only 0.5%. Regionally, the Wooramel Group shows the best hydrocarbon potential in the sub-basin.

The GSWA interpretation (Figs 5 and 20) indicates that the well was not located in an optimal crestal location, at either the top Birdrong Sandstone level or the intra-Permian horizons. The main potential reservoir penetrated in the well was the Moogooloo Sandstone of the Wooramel Group. This unit lies directly below the basal Cretaceous Birdrong Sandstone (Fig. 20) and therefore, is not a viable objective. The Lower Carboniferous – Devonian megasequence, however, remains untested.

Airey Hill 1

Airey Hill 1 was drilled in 1980 by Monarch Petroleum to a total depth of 1032 m on the western flank of the Maud Landing. This feature is a topographic high subparallel to the coastline in the vicinity of Cardabia Homestead. The salient trend, although not structurally mapped, was considered to be anticlinal in nature, similar to the anticlines drilled in the region by WAPET during the early exploration activities of the fifties and sixties. The main objective was the Birdrong Sandstone (Monarch Petroleum NL, 1980). Long-distance migration of hydrocarbons from the Jurassic source rocks to the northwest into the region was considered possible due to the excellent reservoir characteristics of the Birdrong Sandstone.

The well was spudded in Holocene sediments and penetrated mainly calcareous undifferentiated Cainozoic clastic rocks to 400 m. The Upper Cretaceous was intersected from 400 to 816 m and the Lower Cretaceous to 1004 m (Appendix 2). In the well, the Birdrong Sandstone is 70 m thick and mainly represented by sandstone showing very good reservoir characteristics throughout and only thin interbeds of claystone. The uppermost section is considered to be marine, while the lower sandy units are interpreted to be fluvial to marginal marine. Log-derived porosity values range from 29 to 36%, and an analysis of three sidewall-cores showed porosity values ranging from 24.5 to 28.5% and permeability values ranging from 473 to 655 millidarcies (md). At 1004 m the unit rests unconformably on Permian rocks assigned to the Lyons Group (Monarch Petroleum NL, 1980), in which the well was terminated at 1037 m.

No gas shows or fluorescence were noted during drilling. Monarch Petroleum NL (1980) stated that a ‘distinct hydrocarbon odour’ and ‘greasy films’ were noted in the formation water recovered from the interval 936.5–943.5 m. Although the dipmeter indicates low structural dips, GSWA seismic interpretation (Figs 13 and 15) shows that the well was drilled in a westerly dipping monocline.

Garden Mill 1

Garden Mill 1 was drilled by Golden West Hydrocarbons in 1983 to a total depth of 555 m in order to test an interpreted stratigraphic trap in the Birdrong Sandstone. The well was positioned on an updip location within a top Birdrong Sandstone depositional embayment. Basement was expected to provide the bottom seal (Golden West Hydrocarbons Pty Ltd, 1983).

Below the Tertiary a Cretaceous sequence was penetrated from 130 to 529 m (Appendix 2). In this well the Birdrong Sandstone had poorer reservoir character-istics than are present regionally, probably because it is closer to the basin edge, resulting in the deposition of fine-grained sandstone with a high percentage of glauconitic silt. The Birdrong Sandstone unconformably overlies a kaolinitic sandstone that in turn overlies a phyllitic schist. The kaolinitic sandstone was tentatively interpreted by Golden West Hydrocarbons to be undiffer-entiated Palaeozoic; alternatively, it may represent weathered basement. The palynological note attached to the well completion report is considered by the author (B. S. Ingram) to offer a ‘very low level of confidence’.

Garden Mill 1 did not encounter any significant hydrocarbon shows. Formation fluid was recovered from two discrete intervals, 515–526 m and 542–550 m, interpreted to be the Muderong Shale – Birdrong Sandstone and basement respectively. Initial salinities of 5000 ppm NaCl equiv. increased to about 7000 ppm after a flow period. These values indicate that the objective sands have been flushed by meteoric waters.

After drilling, Golden West Hydrocarbons Pty Ltd (1983) considered that an untested very small closure may still be present updip from Garden Mill 1. However, such a trap would be of questionable economic interest. The interpreted pinchout of the Birdrong Sandstone updip from Garden Mill 1 does not necessarily generate an effective trap, since the weathered layers of the basement may not provide an effective bottom seal. Furthermore, resolution of seismic horizons in the Garden Mill 1 area below a strong intra–Muderong Shale marker are problematic. Consequently, mapping the pinchout edge of the Birdrong Sandstone is difficult with these data.

It is concluded that the area tested by Garden Mill 1 is part of the Yanrey–Marrilla High, and offers limited or no hydrocarbon potential.

West Giralia 1

West Giralia 1 was drilled by Golden West Hydrocarbons in 1984–85 to a total depth of 789 m. The objective of the well was to evaluate the hydrocarbon potential of the Birdrong Sandstone in a seismically controlled trap on the western flank of the Giralia Anticline (Golden West Hydrocarbons Pty Ltd, 1985a). As interpreted by Golden West Hydrocarbons Pty Ltd (1985a), the structure was closed to the west by regional dipping, by a north–south local rollover, and to the east by a secondary fault that provided the critical seal updip.

Below a Tertiary limestone, the well penetrated Cretaceous sediments from 192.5 to 712.5 m (Appendix 2). The Birdrong Sandstone unconformably overlies the Wooramel Group (to 742 m), and then the Callytharra Formation to a total depth of 789 m. Core analyses and wireline log evaluation (density and neutron logs) indicate that the porosity of the objective Birdrong Sandstone ranges from 21 to 35%, while permeability data from a core cut between 666 and 675 m with a recovery of 1.7 m, gave values of 150 and 362 md. The reservoir potential of the unit was therefore confirmed. No hydrocarbon shows were indicated by either gas chromatograph, ditch cuttings, core analyses, or wireline log interpretation. Formation water salinity interpreted from logs was 10 000 ppm NaCl equivalent.

From the GSWA seismic interpretation (Figs 13 to 15), West Giralia 1 did not test a valid structural closure.

Whitlock Dam 1

Whitlock Dam 1 was drilled by Golden West Hydrocarbons in 1984–85 to a total depth of 413 m. The primary objective was the Cretaceous Birdrong Sandstone, expected to be within a secondary closure along the north-plunging axis of the Giralia Anticline (Golden West Hydrocarbons Pty Ltd, 1985c). The structural mapping by Golden West Hydrocarbons indicated a four-way dip closure at the well location. Whitlock Dam 1, however, was drilled on a rollover controlled only by a single seismic line along the structural axis of the anticline (Fig. 5). As interpreted, the Whitlock Dam structure demonstrated north–south seismic rollover greater than 20 ms. East–west reversal was deduced from surface data.

Whitlock Dam 1 penetrated a typical Cretaceous sequence to 368.5 m, where the Birdrong Sandstone unconformably overlies the Early Permian Byro Group in which the well was terminated. Log-derived porosity values for the Birdrong Sandstone average 30%.

The GSWA seismic interpretations of the top Muderong Shale level (Fig. 14) and the Early Neocomian unconformity level (Fig. 15) confirm the presence of a structural closure in Whitlock Dam 1. Such a closure represents a secondary high along the structural axis of the Giralia anticline.

No shows of hydrocarbons were encountered in the objective unit. The low log-derived salinity of 2000 ppm NaCl equiv. indicates extensive flushing by meteoric waters, originating either from the Birdrong Sandstone outcrop to the east, or through the Giralia Fault. Analyses of two mud samples from the Gearle Siltstone at 140 m, however, indicate the presence of crude oil. In the geochemical appendix to the well completion report (Golden West Hydrocarbons Pty Ltd, 1985c), R. Alexander states that '...both samples contain a series of n-alkanes extending from C_{11} to C_{30}. Pristane and phytane were also identified. This distribution of n-alkanes and isoprenoid alkanes is characteristic of crude oil and is not typical of petroleum-derived fuels such as diesel'.

The presence of crude oil in the well is attributed to hydrocarbons migrating into the area because potential source rocks near the well are immature. The presence of oil only within the Gearle Siltstone may be related to the poor permeability of the formation. The chances of finding hydrocarbon accumulations of economic interest in the area seem limited to unfaulted closures capable of withstanding strong hydrodynamic gradients.

North Giralia 1

North Giralia 1 was drilled in 1985 by Golden West Hydrocarbons to test a seismically interpreted secondary culmination on the west flank of the Giralia Anticline. The North Giralia culmination was the northernmost trap mapped by Golden West Hydrocarbons along the anticline. The primary objective was the Cretaceous Birdrong Sandstone (Golden West Hydrocarbons Pty Ltd, 1985b).

The well penetrated a Tertiary–Cretaceous section typical of this part of the basin, extending from the surface to the Main Unconformity encountered at 697 m. Golden West Hydrocarbons interpreted a minor fault in the Muderong Shale to account for its reduced thickness. The Birdrong Sandstone was encountered at 644.5 m and an analysis of core cut from 650 to 659 m (80 cm recovered) showed good porosity (20–22%) and horizontal permeability (590–650 md). From the Main Unconformity to the total depth of 936 m a Permian (Artinskian) sequence, tentatively referred to the Byro Group, was penetrated. No hydrocarbon shows were encountered while drilling, nor were hydrocarbons indicated by the electric log interpretation. The salinity of the water in the Birdrong

Sandstone was calculated from the wireline log at 10 000 ppm NaCl equivalent.

The GSWA seismic interpretation of the area (Figs 13 to 15) does not show the presence of a structural trap in the North Giralia area. The lack of a demonstrated east–west rollover may be the result of limited seismic control, since surface data appear to confirm the presence of such a closure (Fig. 20). Closure to the south is not indicated. The lack of a valid trap is suggested and the primary objective appears to have been flushed by meteoric waters.

Sandalwood 1

Sandalwood 1 was drilled in 1990 to a total depth of 1350 m by S.R.L. Exploration, a wholly owned subsidiary of Metana Petroleum. The well was programmed to test the hydrocarbon potential of the Birdrong Sandstone in a seismically defined faulted high. A secondary objective was postulated to exist within the pre-Cretaceous section (Mitchell, 1990). S.R.L. Exploration considered that the Sandalwood structure was controlled by three-way dip closure at the base Cretaceous level, with the critical eastern closure provided by a westerly thrusted reverse fault. The structure is immediately east of the Rough Range Fault.

From the surface to 1169 m Sandalwood 1 en-countered the Tertiary–Cretaceous stratigraphic section typical of the area. The primary objective, the Birdrong Sandstone, was penetrated from 1169 to 1188.5 m (Appendix 2). The Birdrong Sandstone overlies the Wogatti Sandstone, which is present over the North West Cape (Crostella, 1996a) but has not been found in the Giralia area. The Wogatti Sandstone is the product of the regressive fluvio-deltaic cycle following the thick Triassic –Jurassic succession. This unit was deposited over the Exmouth, Barrow, and Dampier Sub-basins of the Northern Carnarvon Basin. Both the Birdrong and the Wogatti Sandstones exhibit excellent reservoir potential. From 1234 to 1332 m the well encountered Permian rocks interpreted by S.R.L. Exploration as the Byro Group, and then Callytharra Formation in which the well was terminated at 1350 m.

An unconformity was interpreted between the Wogatti Sandstone and the Byro Group. S.R.L. Exploration did not comment on the absence of the Wooramel Group, regionally present between the Callytharra Formation and the Byro Group. The presence of the Callytharra Formation was suggested by a Sakmarian age deduced from palaeontologic data. However, the palynological report attached to Mitchell (1990) indicates a Kungurian age, as does the palynological review by the GSWA (Backhouse, J., 1996, pers. comm.). Therefore, it is concluded that in Sandalwood 1 the Wogatti Sandstone overlies either the lower Coolkilya Sandstone (Kennedy Group) or the uppermost Byro Group (Table 2).

No shows of hydrocarbons were noted and no tests were run. Water salinities from logs in the Birdrong and Wogatti Sandstones were 7000–8000 ppm NaCl equiv., which is consistent with salinity trends in the area where flushing of the interval by meteoric waters is common. Total organic carbon (TOC) values for the Permian ranged from 1.1 to 2.3%, but hydrogen indices were low to marginal. Vitrinite reflectance data on Permian samples indicate immature sediments implying that the Permian rocks have not been buried at depths substantially deeper than at present.

An alternative seismic interpretation is presented in Figure 14 following the GSWA structural interpretation. The feature tested by Sandalwood 1 is controlled to the east by an easterly thrusted reverse fault locally sub-parallel to the Rough Range Fault (Fig. 11). Older seismic coverage across the Sandalwood feature (Fig. 26) is of poorer quality than the younger seismic data (Fig. 10), stressing the critical importance of acquisition parameters to properly define structures such as Sandalwood. The GSWA seismic interpretation shows a reverse fault intersecting the well between the Cretaceous Wogatti Sandstone and the Permian Kennedy (or Byro) Group. The upthrown side has a Tertiary–Cretaceous section overlying the Early Neocomian Wogatti Sandstone, consistent with the stratigraphic setting of the North West Cape province. The downthrown side consists of the typical Permian sequence found within the Giralia area. This interpretation is in agreement with the regional setting described by Crostella (1996a). The Rough Range Fault on the western margin of the Sandalwood structure and the subparallel fault to the east are interpreted as en echelon strike-slip faults.

The GSWA seismic map of the top Muderong Shale level (Fig. 14) indicates that Sandalwood 1 tested a small, low-relief, structural closure. The vertical relief of the time closure is, however, so small that it may be invalidated by the velocity problems present on the Rough Range trend (Crostella, 1996a). The positive trend between the two faults described above continues to the southwest of Sandalwood 1 and probably offshore. Onshore, no mapped closure is evidenced by the available seismic control.

Potential petroleum objectives

The 15 petroleum wells drilled to date in the Giralia area do not indicate any hydrocarbon accumulations. Failure to discover hydrocarbons is to a great extent attributable to the fact that many wells drilled in the 1950s and 1960s had inadequate seismic structural control. Furthermore, geochemical data were scarce and poorly understood. Table 3 lists the reasons for the failure of exploration wells to intercept hydrocarbon accumulations at the Birdrong Sandstone level. The table shows that six exploration wells failed to intercept hydrocarbons because of weak trap definition, three probably because of the lack of migration paths from effective source rocks, and four because no seal was present. Two wells were drilled for stratigraphic information. Potential reservoir rocks were present in all wells except Yanrey 1.

Several petroleum exploration objectives are present in the area, namely the Cretaceous Windalia Sand

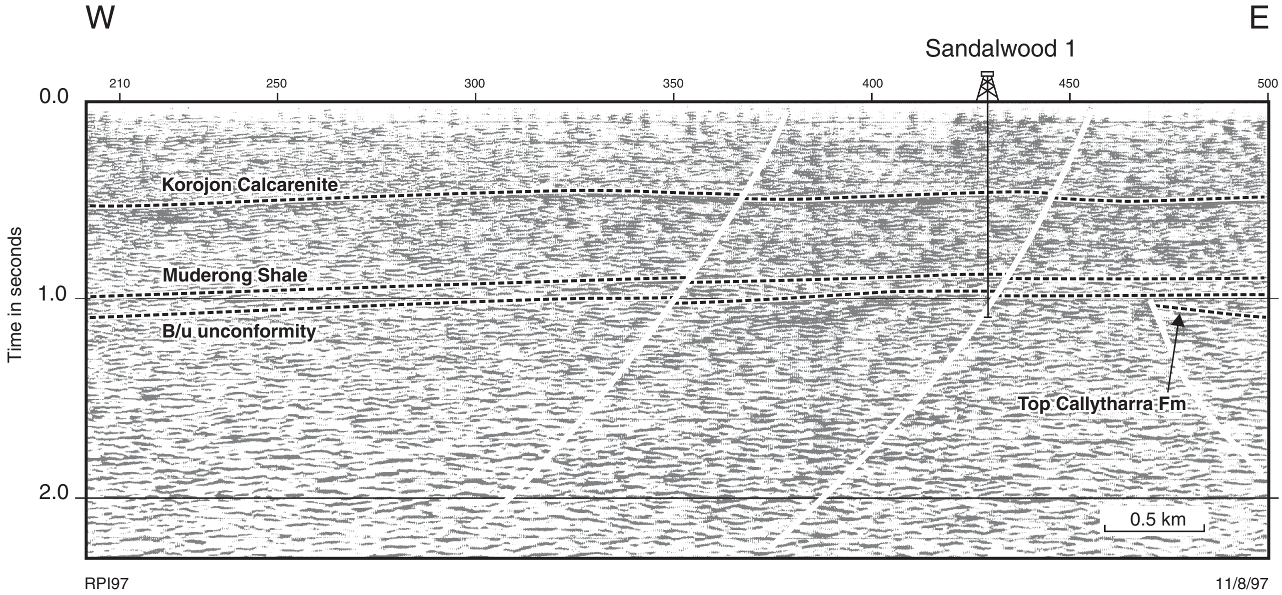


Figure 26. Structural setting of Sandalwood 1 shown with older vintage and poorer quality seismic line A85-10. Line location shown on Figures 13 to 16. B/u unconformity = breakup unconformity in the Early Cretaceous

Member, Birdrong Sandstone, sand units within the Triassic Locker Shale and Mungaroo Formation, the Permian Moogooloo Sandstone, and the Devonian Nannyarra Sandstone.

Windalia Sand Member (Cretaceous)

The Windalia Sand Member contains the largest percentage of the reserves of the Barrow Island oilfield, amounting to 50 million kL. In the Barrow Island oilfield, the porosity of the Windalia Sand Member averages 27%, but permeability averages only 2.5 md. Although the reservoir characteristics of the unit are far from optimal, its retention capabilities are upgraded by the low permeability and lenticular distribution of the reservoir. The factors controlling the geographic distribution of the Windalia Sand Member are poorly known and its presence cannot be predicted with any confidence since lateral facies changes are numerous. The unit, or a time-equivalent, is also present in the Robe River area and in Giralia 1. Consequently, the Windalia Sand Member may be present in the northern part of the Giralia area. Many wells were drilled prior to recognition of the Windalia Sand Member, so its extent is probably wider than is apparent from the literature.

In the region the Jurassic Dingo Claystone has been demonstrated to be the main source rock for hydrocarbons. However, long-range migration is required because Jurassic rocks are not present in the Giralia area. The best indication for such migration is provided by Whitlock Dam 1 where oil has been found in the drilling mud while penetrating the Gearle Siltstone. Absence of hydrocarbon discoveries in the more porous and permeable Birdrong Sandstone suggests that the migrating oil was not trapped at this level but possibly migrated into higher stratigraphic intervals. No traps in the Windalia Sand Member have been identified in the area where the play is considered to be present, but additional detailed seismic surveys are required to define

Table 3. Interpreted reasons for wells in the Giralia area failing to intercept hydrocarbon accumulations in the Birdrong Sandstone

Unproven trap	*Lack of effective source rocks*	*No effective seal*	*Stratigraphic well*
Airey Hill 1	Warroora 1	Giralia 1	Marrilla 1
Garden Hill 1	Chargoo 1	Witlock Dam 1	Hope Island 1
West Giralia 1	Gnaraloo 1	Remarkable Hill 1	
North Giralia 1		Sandalwood 1	
East Marrilla 1			
BMR 5 Giralia			

possible, but as yet unidentified, closures. The Windalia Sand Member is considered to be a high-risk play but this is offset by the low costs of shallow wells and an onshore operation.

Birdrong Sandstone (Cretaceous)

The Birdrong Sandstone is an excellent potential reservoir because of its consistently high porosity and permeability, reaching 28.5% and 655 md respectively (measured from sidewall cores). In addition, facies equivalents of the Birdrong Sandstone in the majority of the inner Barrow Sub-basin oilfields contain hydrocarbons. Unfortunately, in the Giralia Anticline the unit is very shallow and is above sea level at its highest crestal point, tested by Giralia 1. An outcrop of the Birdrong Sandstone near Giralia 1 on the Giralia Anticline (McLoughlin et al., 1995) demonstrates that there is no effective seal at this location. Furthermore, the high permeability and lateral continuity of the unit allows fluid movement over long distances, as demonstrated by the low salinity of water in the Birdrong Sandstone over the entire area. Water samples from Giralia 1, Marrilla 1, Hope Island 1, Remarkable Hill 1, Garden Mill 1, and Whitlock Dam 1 confirm that the water in the unit is flushed.

Top seal integrity risks are reduced where the Birdrong Sandstone is deeper than about 1000 m. One such area may be near Sandalwood 1. Figure 14 shows that in the Sandalwood 1 area the top of the Muderong Shale rises to the southwest and is closed by dips to the west and east, with one of the transfer faults oriented at 320° providing the critical closure to the southwest. The proximity of the Mesozoic series, comprising the Jurassic source rocks, suggests that there is a good possibility of hydrocarbons migrating into the area. It is concluded that the Birdrong Sandstone is still a valid objective in the Sandalwood area.

Locker Shale and Mungaroo Formation (Triassic)

Sandstone penetrated within the Lower Triassic Locker Shale in Hope Island 1 contains good reservoir characteristics that have also been located in wells drilled to the north. Similar good reservoir characteristics are indicated within the overlying Mungaroo Formation. On regional grounds, the Locker Shale is also expected to have good source-rock potential. The Triassic objectives are only present in the northernmost part of the Giralia area, where seismic control is scarce. It is possible that a truncation or fault block play could be present here. A truncation play would, however, rely on transgressive lowermost Cretaceous strata providing a top seal. In fault blocks the seal may be provided by the Locker Shale itself or by intraformational shale within the Mungaroo Formation. A truncation play, in which Triassic and Jurassic reservoirs abut against the Rough Range Fault, is possible in this area.

Moogooloo Sandstone (Permian)

The Moogooloo Sandstone is regionally a good potential reservoir (Havord, in prep.). The Wooramel Group, which includes the Moogooloo Sandstone, has good source rock potential (Ghori, 1996); however, geochemical data from Giralia 1 (Fig. 24), Remarkable Hill, and Sandalwood 1 indicate that the Wooramel Group in the Giralia area is largely immature.

In Giralia 1 and Remarkable Hill 1 fluid inclusion analyses of the Moogooloo Sandstone detected oil (Eadington, 1997). In Giralia 1 the oil has been found to be mature, whereas in Remarkable Hill 1 the oil is either immature or biodegraded. The Moogooloo Sandstone should therefore be included as a potential objective in the Giralia area.

Nannyarra Sandstone (Devonian)

The Nannyarra Sandstone in Gneudna 1 has good reservoir potential, with porosity ranging from 8.2 to 19.4% and permeability up to 55.2 md (Mory, 1996). As in Gneudna 1, Quail 1, and Wandagee 1, the thickness of the formation may exceed 100 m.

In Gneudna 1 the shale between 297 and 303 m has good source potential for oil (Mory and Backhouse, 1997). As this interval is within the Gneudna Formation, which conformably overlies the Nannyarra Sandstone, the validity of the latter as an oil exploration objective is, at least locally, demonstrated. The Nannyarra Sandstone would be sealed by overlying impervious strata of the Gneudna Formation. More information is required to evaluate the hydrocarbon potential of the Nannyarra Sandstone in the Giralia area. The Geological Survey of Western Australia is planning to acquire further data on the source potential of the Devonian in the Gascoyne Platform where the Devonian is at a shallow depth. Source rock potential, however, has been demonstrated in Devonian and, where present, Silurian rocks (Dolan and Associates, 1991). The attractiveness of the Devonian section in the Giralia area is increased by the possible reservoir potential of the Gneudna Formation, albeit difficult to quantify. The possibility of reef development within the Gneudna Formation has been discussed by Geary (1970) and Hocking et al. (1987). It is noteworthy that Gneudna 1 intersected a vuggy dolomite with 9.3% porosity and 10.5 md permeability (Mory, 1996).

Regional petroleum potential

The Windalia Sand Member is present only locally and its distribution is difficult to predict. Conversely, the localized presence of the unit increases its retention potential, especially for oil, as meteoric flushing is not facilitated. The presence of hydrocarbons, albeit minor, in Whitlock Dam 1, Giralia 1, Remarkable Hill 1, and Gnaraloo 1 demonstrate migration of oil within the area. Minor untested traps are expected to be present.

The Birdrong Sandstone, with its good reservoir characteristics, is widespread but regionally cannot be considered an attractive objective. In the area of the Salt Marsh anticlines (Figs 2 and 18) the Birdrong Sandstone is expected to be outside the migration range from the likely Jurassic source-rocks area. In addition, the top seal of the Birdrong Sandstone is questionable because of possible breaching. Lateral water flushing represents another risk factor. In the main Giralia area the regional distribution and high permeability of the unit allows updip migration to shallow crestal positions. Hydrocarbons were not trapped at the crest of these structures due to either the lack of an effective seal at such shallow depths or to water flushing. The low salinity of the Birdrong Sandstone water, wherever tested or logged, indicates either one or both of these occurrences. Effective traps may, however, be present in localized areas; for example in the Sandalwood area, where the unit is substantially deeper and the potential for a closed trap exists.

The Triassic objectives are conceptually valid only in the northernmost part of the Giralia area. The Permian Moogooloo Sandstone offers limited attractiveness, even though the remainder of the Wooramel Group contains potential source rocks. Studies by GSWA indicate that Permian source rocks are regionally immature, but white-fluorescing inclusions within the Moogooloo Sandstone from Giralia 1 are consistent with oil expelled from source rocks at peak oil generation. However, predominantly yellow- and orange-fluorescing inclusions within the Moogooloo Sandstone from Burna 1, Quail 1, Kennedy Range 1, and Remarkable Hill 1 are consistent with oil expelled from source rocks at the onset of oil generation (Eadington, 1997).

Two large untested features make the Devonian objectives attractive, especially the Nannyarra Sandstone. These features are the structural high indicated immediately to the southeast of the Rough Range Anticline near Rough Range South 5 (Fig. 2), and the anticline drilled to a Permian level by Giralia 1 and Remarkable Hill 1 (Fig. 20, Section B–B').

Conclusions

Cretaceous, Permian, and Devonian objectives for hydrocarbon exploration are present within the Giralia area in the onshore Carnarvon Basin. Several wells in the area encountered hydrocarbons within the Windalia Sand Member, which is the main reservoir in the Barrow Island oilfield — the biggest oilfield in Western Australia. The Lower Cretaceous Birdrong Sandstone is also an attractive objective because of the good reservoir characteristics, although poor trapping conditions downgrade its economic viability. Indications of oil within the Lower Permian Moogooloo Sandstone from several wells in the Giralia area suggest that this formation is also a viable objective. Although Devonian source and reservoir rock potential have been proven in the area, as yet such objectives are untested.

Following the euphoric exploration activity that took place in the area when oil was discovered in Rough Range 1 in 1953, most of the oil exploration wells in the Giralia area were drilled on unproven traps or solely for stratigraphic information, when regional geological knowledge and exploration technology were still developing. Untested structural highs have been demonstrated adjacent to major faults that may provide vertical conduits for migrating hydrocarbons. The southern part of the Giralia area, characterized by the Salt Marsh anticlines, does not have adequate seismic coverage, but suitable traps may be present below the breakup unconformity. By analogy with the area to the north, the outcropping asymmetric Miocene anticlines are probably the result of rejuvenated breakup faults. These faults may not have been recognized because they do not reach the surface or are covered by Quaternary sediments.

This report provides an updated understanding of the regional geology. An exploration program applying this new knowledge, together with the use of the latest techniques, should provide better definition of the structural setting of the Giralia area, which may then lead to hydrocarbon discoveries of economic significance.

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Appendix 1

Oil exploration well completion reports utilized and their drilling objective

Well name	*Operator*	*Year*	*Total depth (m)*	*Objective*	*S No.*
Rough Range 1	WAPET	1953/55	4 452.2	Birdrong Sandstone, pre-Cretaceous stratigraphic test	51 V13
Giralia 1	WAPET	1955	1 244	Birdrong Sandstone	51
Warroora 1	WAPET	1955	1 826	Birdrong Sandstone, pre-Cretaceous stratigraphic test	51
Rough Range South 5	WAPET	1956	1 451.5	Birdrong Sandstone	51 V28
Yanrey 1	WAPET	1957	431	Stratigraphic test	51
BMR 5 (Giralia)	BMR	1958	631	Stratigraphic test	published
Marrilla 1	WAPET	1963	457	Stratigraphic test	70
East Marrilla 1	WAPET	1963	405	Birdrong Sandstone	110
Whaleback 1	WAPET	1963	1 528	Birdrong Sandstone – Jurassic–Permian	68
Quail 1	WAPET	1963	3 580	Permian–Carboniferous–Devonian–Silurian	67
Chargoo 1	WAPET	1967	428	Birdrong Sandstone	389
Gnaraloo 1	WAPET	1967	502	Birdrong Sandstone	390
Hope Island 1	WAPET	1968	1 417	Birdrong Sandstone, Kennedy Group	412
Remarkable Hill 1	Marathon	1969	3 206	Palaeozoic rocks	443
Airey Hill 1	Monarch	1980	1 037	Birdrong Sandstone	1629
Garden Mill 1	Golden West	1983	555	Birdrong Sandstone	2667
West Giralia 1	Golden West	1984/85	789	Birdrong Sandstone	2699
Whitlock Dam 1	Golden West	1984/85	413	Birdrong Sandstone	2744
North Giralia 1	Golden West	1985	936	Birdrong Sandstone	2731
Burna 1	Esso	1985		Moogooloo Sandstone	629
Lefroy Hill 1	Ampolex Ltd	1986	1 512	Birdrong Sandstone	2936
Tent Hill 1	Minora	1989	580	Birdrong Sandstone	3702
Sandalwood 1	SRL	1990	1 350	Birdrong Sandstone	3993

NOTES:
BMR: Bureau of Mineral Resources
Esso: Esso Exploration and Production Australia Inc.
Golden West: Golden West Hydrocarbons Pty Ltd
Marathon: Marathon Petroleum Pty Ltd
Minora: Minora Resources NL
Monarch: Monarch Petroleum NL
S No.: Geological Survey of Western Australia S-series number
SRL: S.R.L. Exploration Pty Ltd (subsidiary of Metana Petroleum NL)
WAPET: Western Australia Petroleum Pty Ltd

Appendix 2

Formation tops of petroleum wells in the Giralia area

Well	*KB/RT*	*GL*	*Q–T*	*Kk*	*Kt*	*KWg*	*KWw*	*KWm*	*Kwb*	*Ko*	*J*	*Rl*	*PK*	*PB*	*PBc*	*PW*	*PWb*	*PWm*	*PWc*	*Pc*	*CPL*	*C*	*Cq*	*Cm*	*D*	*pE*	*TD*
Airey Hill 1	72	68	4	495	541	625	816	902	934	–	–	–	–	–	–	–	–	–	–	–	1 004	–	–	–	–	–	1 037
BMR 5, Giralia	74	720	–	2	35	80	314	392	460	–	–	–	–	479	–	–	–	–	–	–	–	–	–	–	–	–	631
Burna 1	87	81	–	–	–	–	–	–	–	–	–	–	–	14	24	–	224	396	512	575	740	–	–	–	–	–	768
Chargoo 1	28	27	1	–	–	142	299	360	366	–	–	–	–	–	–	–	–	–	–	–	409	–	–	–	–	–	428
East Marrilla 1	62	59	3	–	–	30	124	253	311	–	–	–	–	–	–	–	–	–	–	–	375	–	–	406	–	–	639
Garden Mill 1	12	10	2	3	130	187	397	461	522	–	–	–	–	–	–	–	–	?529	–	–	–	–	–	–	–	544	555
Giralia 1	112	110	–	–	–	–	2	30	104	–	–	–	–	–	117	–	481	690	866	944	1 208	–	–	–	–	–	1 244
Gnaraloo 1	48	46	2	–	49	211	355	402	410	–	–	–	–	–	–	–	–	–	–	–	–	–	450	–	–	–	502
Hope Island 1	9	5	4	–	352	428	786	838	890	–	–	912	997	–	–	–	–	–	–	–	–	–	–	–	–	–	1 427
Lefroy Hill 1	22	14	10	590	637	647	1 267	1 311F																			
							1 332F	1 375	1 401	–	1 406	–	1 486	–	–	–	–	–	–	–	–	–	–	–	–	–	1 512
Marrilla 1	49	47	2	–	–	29	235	317	382	–	–	–	–	–	–	–	–	–	–	–	–	411	–	–	–	–	457
North Giralia 1	23	20	3	149	201	262	576	599	645	–	–	–	–	697	–	–	–	–	–	–	–	–	–	–	–	–	936
Remarkable Hill 1	111	107	–	–	–	4	79	183	256	–	–	–	–	–	–	–	273	459	601	695	899	–	–	–	–	–	3 206
Rough Range 1	61	57	4	403	425	437	1 023	1 059	1 098	1 109	1 216	–	–	–	–	–	–	–	–	–	1 897	–	–	–	3 263	–	4 452
Rough Range South 5	109	106	3	449	494	525	1 080	1 087	1 149	1 164F																	
								1 243F	1 271	1 287	–	–	–	–	–	–	–	–	–	–	1 386	–	–	–	–	–	1 451
Sandalwood 1	52	48	4	660	701	738	1 046	1 121	1 169	1 189	–	–	?1 234	?1 234	–	–	–	–	–	–	–	–	–	–	–	–	1 350
Tent Hill 1	8	5	3	–	112	198	474	520	532	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	572	580
Warroora 1	29	26	–	3	70	117	261	325	331	–	–	–	–	–	–	–	–	–	–	–	343	1 509	–	–	–	–	1 826
West Giralia 1	43	40	3	141	193	278	563	587	665	–	–	–	–	–	–	713	–	–	–	742	–	–	–	–	–	–	789
Whaleback 1	57	54	3	593	651	694	1 070	1 107	1 160	1172	1 233	–	–	–	–	–	–	–	–	1 388	–	–	–	–	–	–	1 528
Whitlock Dam 1	148	145	3	–	–	10	269	290	369	–	–	–	–	390	–	–	–	–	–	–	–	–	–	–	–	–	413
Yanrey 1	16	14	2	98	145	175	405	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	422	431

NOTES:
C: Lower Carboniferous
Cm: Moogooree Formation
CPL: Lyons Group
Cq: Quail Formation
D: Devonian
F indicates reverse fault and sequence is repeated
GL: Ground Level
J: Jurassic
KB/RT: Kelly Bushing/Rotary Table
Kk: Korojon Calcarenite
Ko: Wogatti Sandstone
Kt: Toolonga Calcilutite
KWb: Birdrong Sandstone
KWg: Gearle Siltstone
KWm: Muderong Shale
KWw: Windalia Radiolarite
PB: Byro Group
PBc: Coyrie Formation
Pc: Callytharra Formation
pE: Precambrian
Picks for Burna 1, Giralia 1, and Remarkable Hill 1 have been revised by Mory and Backhouse (1997)
PK: Kennedy Group
PW: Wooramel Group
PWb: Billidee Formation
PWc: Cordalia Sandstone
PWm: Moogooloo Sandstone
Q–T: Quaternary–Tertiary
Rl: Locker Shale
TD: Total depth

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Appendix 3

Seismic surveys conducted in the Giralia area

Survey name	*Year*	*Company*	*Permits*	*S. No*	*No. lines*	*Line km*	*Line prefix*	*WAPEX prefix*
Giralia	1952	WAPET	PE-246-H	S1293	4	46.67	G-B	Giralia
Mia Mia	1968	Marathon	PE-260-H	S392	31	1 431	MM-68	MM-68
Goanna Hill	1982	Monarch Petroleum	EP-166	S1992	4	36	MGH82A	MGH 82A
Bullara	1985	Golden West Hydrocarbons	EP-166	S2907	9	242	85	85
Giralia North	1985	Golden West Hydrocarbons	EP-166	S2655	7	177	84	84
Bullara 2	1986	Golden West Hydrocarbons	EP-166	R1S2996	6	202	86	86
Fishermans Point	1987	Cape Range NL	EP-166	S3234	24	198.1	87	87
Sandalwood	1989	SRL Exploration	EP-166	R1S3443	16	150	SC89	SC89
Salt Marsh	1962	WAPET	PE-28H	S38A1	8		Minilya	Minilya

NOTES: S. No Geological Survey of Western Australia S-series number
WAPEX Western Australia Petroleum Exploration database

Appendix 4

Water bores that penetrated the pre-Cretaceous section in the Giralia area

Bore	*Year*	*Interval (metres)*	*Stratigraphic unit*
Cardabia 1[a] (Deep)	1910–1911	298–368	Byro Group
		368–613	Wooramel Group
		613–854	Callytharra Formation
		854–1223 (TD)	Lyons Group
Cardabia 2[a] (Deep)		165–308	Byro Group
		308–442	Wooramel Group
		Fault	
		442–549	Callytharra Formation
		549–764 (TD)	Lyons Group
Cardabia 3[a] (Mauds Landing Bore)		716–720 (TD)	Grey shale referred to undifferentiated Palaeozoic
Cardabia 4[b]		740–743 (TD)	Grey shale, probably Palaeozoic
Mia Mia 2[a]		242–403 (TD)	Permian
Mia Mia 3[b]	1920	206–211 (TD)	Permian
Mia Mia 6[b]	1928	240–402 (TD)	Permian (Lyons Group)
Minilya 9 (Kooraline) [b]	1910–1912	426–517 (TD)	?Permian
Winning 2 (Dud Bore) [a]		319–613 (TD)	Permian

NOTES: TD total depth

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