STRUCTURAL EVOLUTION AND HYDROCARBON POTENTIAL OF THE MERLINLEIGH AND BYRO SUB-BASINS CARNARVON BASIN, WESTERN AUSTRALIA

by A. Crostella

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Cover picture: **Muderong Fault on the western margin of the Merlinleigh Sub-basin. View from the northwest of the dark-coloured Kennedy Group (Permian) in Big Hill, upthrown in respect to the lighter-coloured Winning Group (Cretaceous) on the right. Photograph by A. J. Mory.**

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Structural evolution and hydrocarbon potential of the Merlinleigh and Byro Sub-basins, Carnarvon Basin, Western Australia

by

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Abstract

In the western part of the Merlinleigh Sub-basin, outcrop, magnetic, gravity, seismic, and well data suggest that rift-related tensional Palaeozoic tectonism is overprinted by Tertiary compression and tectonism, with E–W shortening. Anticlines thought to have formed in the Miocene are widespread in the western section of the sub-basin and are considered to be related to strike-slip movements.

The eastern part of the Merlinleigh Sub-basin and the Byro Sub-basin are less known. Their hydrocarbon potential may be comparable to that of the drilled portion of the Merlinleigh Sub-basin, but additional data are required in order to make conclusive assessments.

Geochemical studies confirm the good source potential of the Permian Wooramel Group both for gas and oil in the northern half of the Merlinleigh Sub-basin. The Devonian Gneudna Formation also has potential to generate hydrocarbons and is more oil prone than the Wooramel Group. As a result of their basinal position the maturity of the source rocks varies greatly. The Devonian rocks are confirmed to be overmature in Quail 1, but are only marginally mature along the eastern margin of the Merlinleigh Sub-basin. The Permian rocks typically range from immature to marginally mature, with the exception of the Kennedy Range 1 area, where they appear to be overmature. Hydrocarbons are still being generated in the region or are re-migrating from existing accumulations.

The two most attractive hydrocarbon plays are the Devonian sandstones of the Nannyarra Sandstone that are covered and sourced by the shales of the Gneudna Formation, and the Permian sandstones of the Moogooloo Sandstone and possibly the Billidee Formation sealed by the Coyrie Formation and sourced by the entire Wooramel Group. The few wells that have been drilled for hydrocarbon exploration in the area do not exhaustively evaluate its hydrocarbon potential. A number of structural traps are still awaiting adequate evaluation.

KEYWORDS: structural geology, Palaeozoic, rift zone, Tertiary, strike slip faults, anticlines, source rock analysis, maturation, hydrocarbon potential.

Introduction

This study is part of the Petroleum Initiatives program being conducted by the Geological Survey of Western Australia (GSWA). This regional review will be followed by more analytical studies, which will also incorporate new data currently being acquired. A preliminary list of the projects planned to date for the Western Margin area is attached as an appendix to this Report.

Permian sedimentary rocks in the Cooper Basin, South Australia, and the Perth and Canning Basins, Western Australia, are hydrocarbon bearing. A continuous belt of Permian deposits flank the western edge of the Yilgarn Craton for its entire length in Western Australia (Fig. 1). Within this belt, closely correlatable stratigraphic sequences are present throughout the Early Permian (Fig. 2). By analogy with the Perth Basin, a re-evaluation of the hydrocarbon prospectivity of the Merlinleigh Sub-basin is presented here, based on a review of both published and unpublished work. Additionally, a preliminary assessment of the hydrocarbon prospectivity of the Byro Sub-basin is made.

The geology and hydrocarbon potential of the north Perth Basin have been reviewed recently by Mory and Iasky (in prep.) and Crostella (1995). The regional geology of the Merlinleigh and Byro Sub-basins was discussed in the context of the Carnarvon Basin by Hocking et al. (1987) and a comprehensive review of the Merlinleigh Sub-basin, focusing on the petroleum geology, was produced by Percival and Cooney (1985). The hydrocarbon potential of the Merlinleigh Sub-basin was further reviewed by Warris (1991) for Doral Resources NL. More recently, Warris (1994) described the hydrocarbon
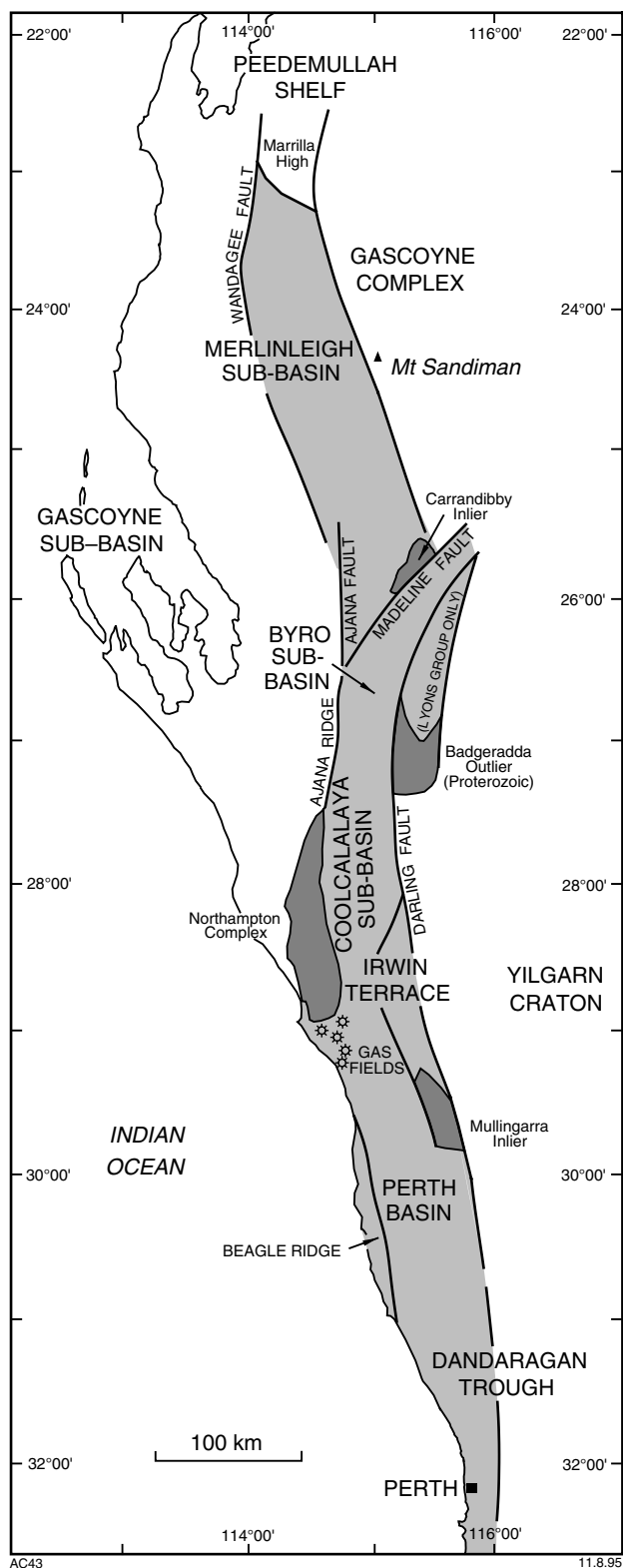
Figure 1. Index map showing the belt of Permian deposits
within the Merlinleigh, Byro, and Coolcalalaya
Sub-basins, and the Perth Basin, which flank the
Yilgarn Craton to the west (after Hocking, 1994)

potential of the Carnarvon Basin megasequences and
Gorter et al. (1994) carried out a similar study of the
Early Palaeozoic sequences of the Carnarvon Basin.

Within the GSWA, work on the area is currently being
carried out by R. P. Iasky, among others, who produced
a Bouguer-anomaly map, in contour and image forms,
and by A. Ghori, who has made preliminary inter-
pretations of geochemical data. This new interpretation
of the structural setting of the Merlinleigh Sub-basin has
also benefitted from a field trip under the guidance of
R. M. Hocking.

Regional framework

The Merlinleigh Sub-basin is characterized by a north-
northwesterly elongated Late Carboniferous to Early
Permian downwarp, which lies between longitudes
114°20'E and 115°00'E. The Late Carboniferous age is
inferred on the basis of regional considerations, although
no direct palaeontological support has yet been provided
(Hocking et al., 1987). To the north, the Merlinleigh Sub-
basin is separated from the Peedamullah Shelf by the ill-
defined Marrilla High. To the east, the depositional
boundary of the downwarp is marked by the transgression
of Late Carboniferous to Early Permian sedimentary rocks
either over Devonian deposits, in the north, or over
Precambrian rocks of the Gascoyne Complex, south of the
Lyons River. In outcrop, the Devonian and Early
Carboniferous deposits overlie Precambrian rocks. To the
south, Permian sedimentary rocks of the Merlinleigh Sub-
basin are either separated from rocks of the same age and
facies in the Byro Sub-basin by the Madeline Fault System
or they unconformably overlie Precambrian rocks of the
Carrandibby Inlier.

The Byro Sub-basin trends northeast in its northern
segment, and changes gradually to a northerly trend in
the southern segment. Magnetic and gravity images
(Figs 3 and 4) suggest that there is no clear boundary
between the Byro and the Coolcalalaya Sub-basins. The
separation of the two sub-basins is based on historical
reasons, but the division cannot be justified on the sparse
outcrop in the two areas. For the purpose of the present
study, the Early Permian Byro Sub-basin and the
Coolcalalaya Sub-basin represent a single depositional
feature. The study area extends south to latitude 27°15'S,
but the Early Permian downwarped sub-basin extends
further to the south where it is intensely faulted and is
connected with the Irwin Terrace.

The eastern boundary of the Byro and Coolcalalaya
Sub-basins is marked by the Meeberrie Fault to the north
and the Darling Fault to the south (Fig. 4). To the west,
the boundary of the Byro and Coolcalalaya Sub-basins is
controlled from south to north by the Northampton
Complex, the Yandi Fault, and the Ajana Ridge.

The western boundary of the Merlinleigh Sub-basin
is represented by the Ajana Fault System in the south,
whereas further to the north basal Late Carboniferous to
Early Permian sedimentary rocks of the Lyons Group
transgress the Devonian to Early Carboniferous sequence
of the Gascoyne Platform. In a limited area in the
northwest the lowermost sedimentary rocks are Silurian.
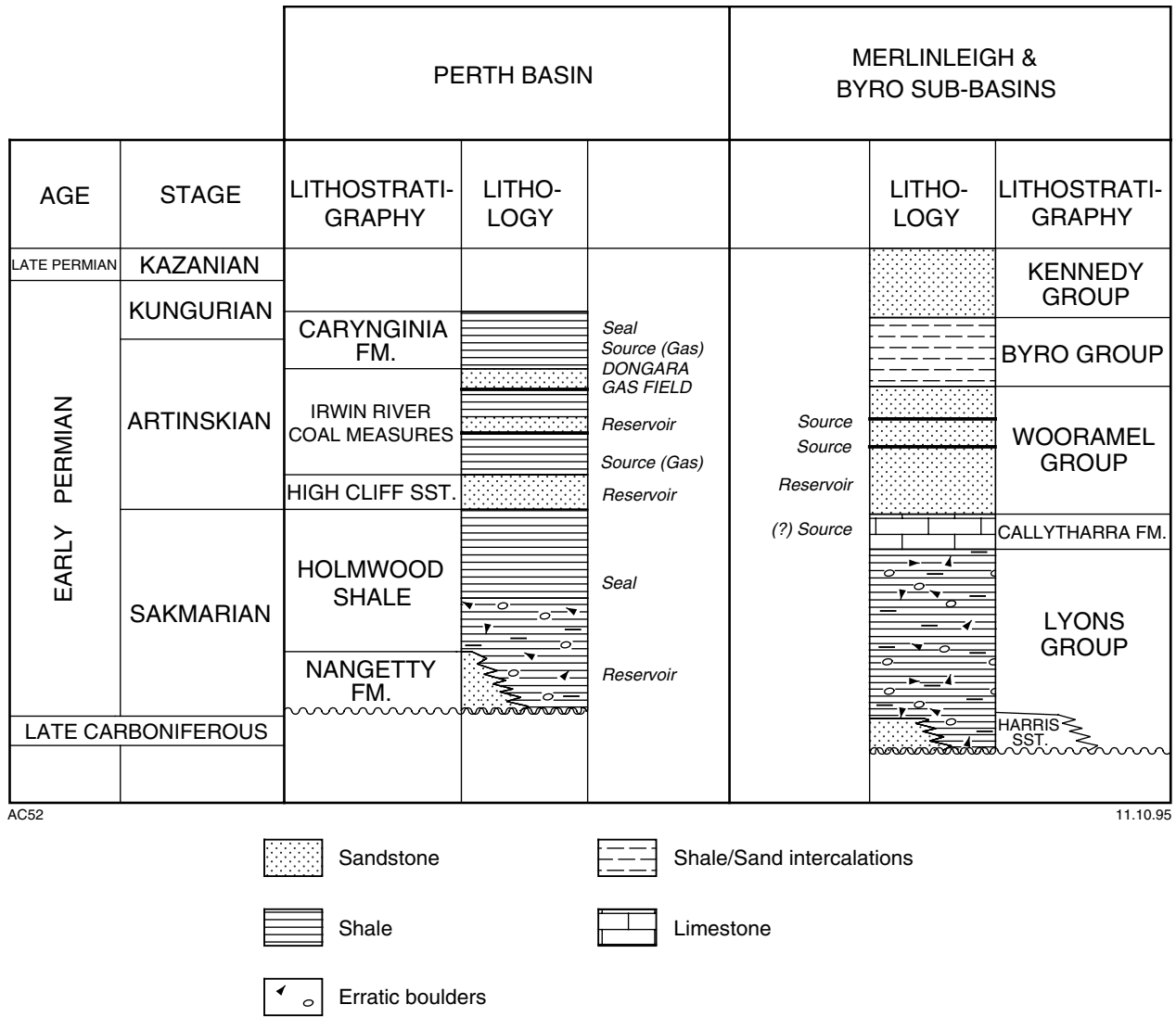Further north, the Permian sequence is depositionally

		PERTH BASIN				MERLINLEIGH & BYRO SUB-BASINS	
AGE	STAGE	LITHOSTRATI-GRAPHY	LITHO-LOGY			LITHO-LOGY	LITHOSTRATI-GRAPHY
LATE PERMIAN	KAZANIAN						KENNEDY GROUP
EARLY PERMIAN	KUNGURIAN	CARYNGINIA FM.		*Seal Source (Gas) DONGARA GAS FIELD*			BYRO GROUP
	ARTINSKIAN	IRWIN RIVER COAL MEASURES		*Reservoir*	*Source*	*Source*	WOORAMEL GROUP
				Source (Gas)	*Source*		
		HIGH CLIFF SST.		*Reservoir*	*Reservoir*		
	SAKMARIAN	HOLMWOOD SHALE		*Seal*	*(?) Source*		CALLYTHARRA FM.
							LYONS GROUP
		NANGETTY FM.		*Reservoir*			
	LATE CARBONIFEROUS						HARRIS SST.

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Legend:

- Sandstone
- Shale
- Erratic boulders
- Shale/Sand intercalations
- Limestone

Figure 2.   Stratigraphic correlation between the Early Permian sequences of the Perth Basin and the Merlinleigh and Byro Sub-basins

continuous with the Permian of the Remarkable Hill area (northwestern Gascoyne Sub-basin), and with the western section of the Peedamullah Shelf, where sedimentation continued into the Mesozoic. The Wandagee Ridge partially interrupts the continuity between the two regions, and probably represents an old high where Carboniferous to Permian sediments were probably never deposited or were very thin. The Wandagee Ridge is historically taken to represent the northwestern boundary of the Merlinleigh Sub-basin.

The Merlinleigh 'downwarp' is filled primarily by Late Carboniferous to Early Permian sedimentary rocks that overlie Devonian to Early Carboniferous sedimentary rocks in the northern half of the sub-basin and Precambrian rocks in the southern half. The older Silurian–Ordovician sequence has only been documented in Quail 1. In the Byro Sub-basin, including part of the area historically referred to as the Coolcalalaya Sub-basin, the Carboniferous to Early Permian sequence directly

transgressed the Precambrian basement. Locally, in the Badgeradda area, unprospective Proterozoic sandstones and siltstones underlie the Late Palaeozoic sedimentary rocks (Perry and Dickins, 1960). The substratum of the almost entirely concealed Coolcalalaya Sub-basin is considered to consist of Silurian and Devonian rocks in its western part (Hocking et al., 1987).

The oldest sedimentary formation intersected by drilling in the Merlinleigh Sub-basin is the Tumblagooda Sandstone, which was penetrated by Quail 1 (Fig. 5). The unit has been variously assigned to the Silurian (Pudovskis, 1962; Hocking et al., 1987) and, more recently, Ordovician (Warris, 1994) or Cambro-Ordovician (Gorter et al., 1994). The drilled sequence consists of very fine-grained quartzite sandstone, grading to siltstone, which is highly radioactive in the upper part (Pearson, 1964). In Quail 1, the Tumblagooda Sandstone is overlain by dolomite, anhydrite, siltstone, and minor sandstone and shale of the Silurian Dirk Hartog Formation (Pearson, 1964). The
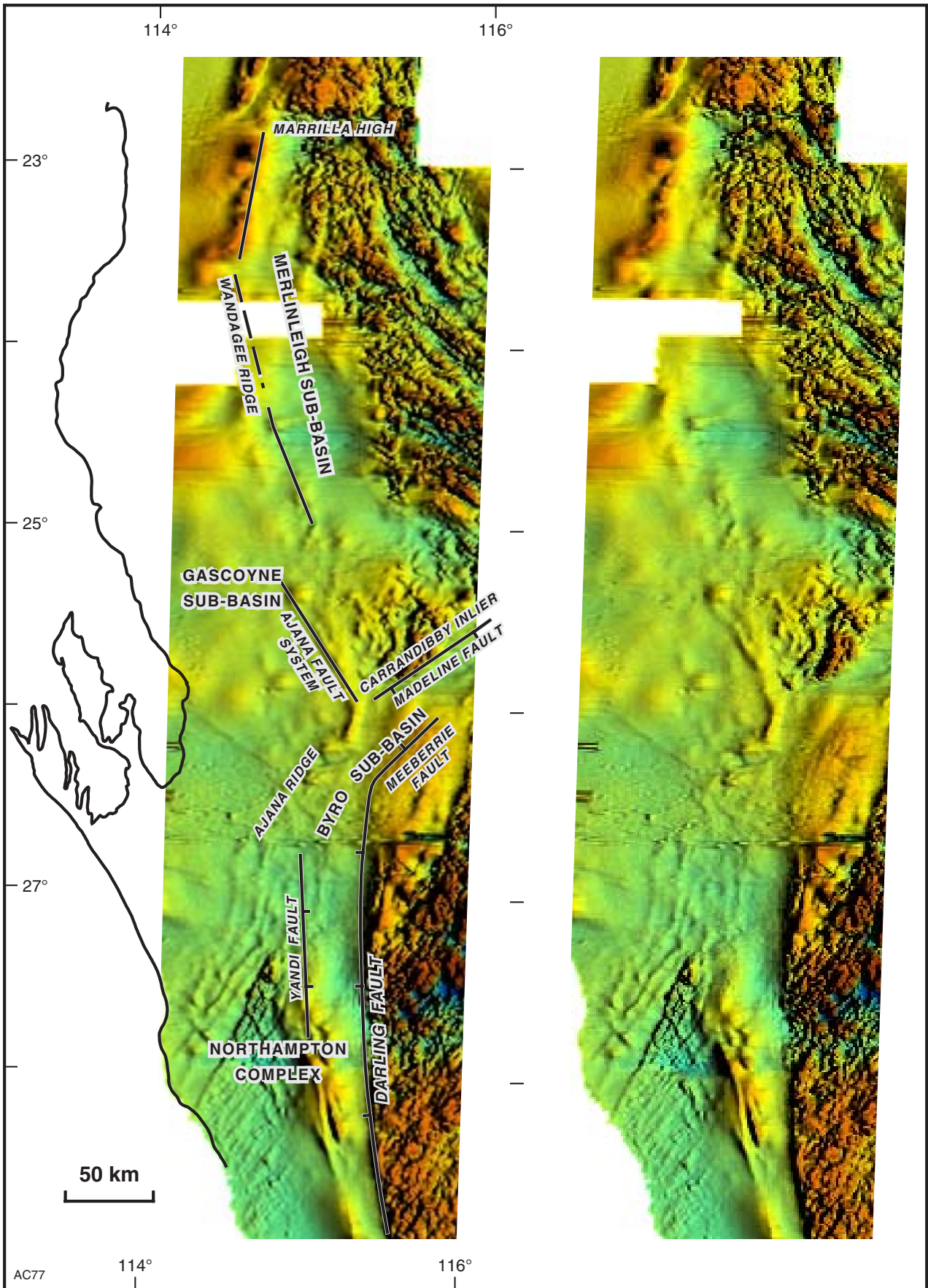
Figure 3. Magnetic image of the Merlinleigh and Byro Sub-basins
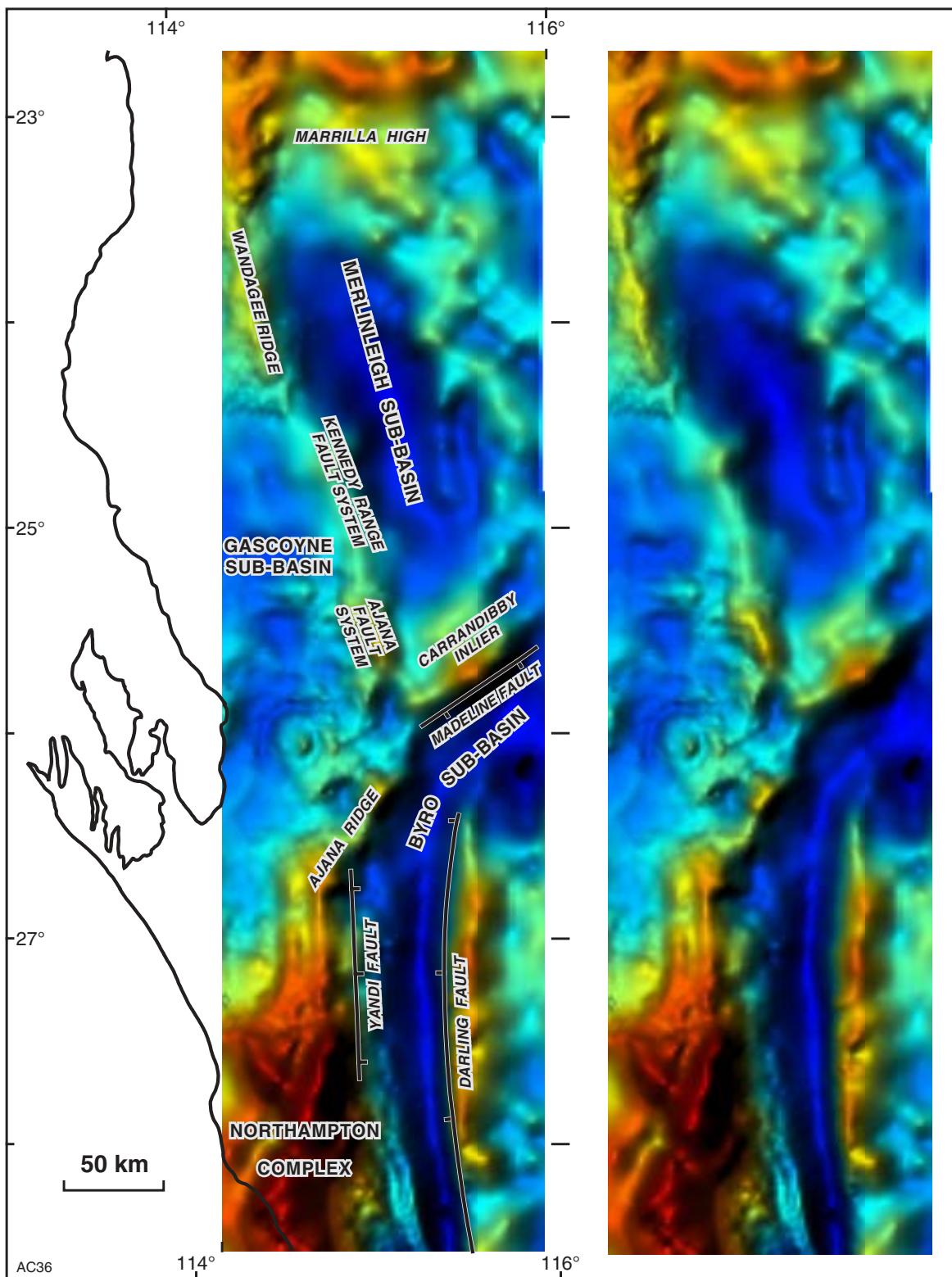
Figure 4. Gravity image of the Merlinleigh and Byro Sub-basins (created from AGSO database)

distribution and depositional history of the Tumblagooda Sandstone and Dirk Hartog Formation within the Merlinleigh Sub-basin were reassessed by Warris (1994) and Gorter et al. (1994) and are not discussed further here.

Within the Merlinleigh Sub-basin three depositional mega-cycles can be differentiated above the Silurian sequence: Devonian to Early Carboniferous, present only north of 24°30'S, being the southernmost outcrops on the northern slopes of Mount Sandiman; Late Carboniferous
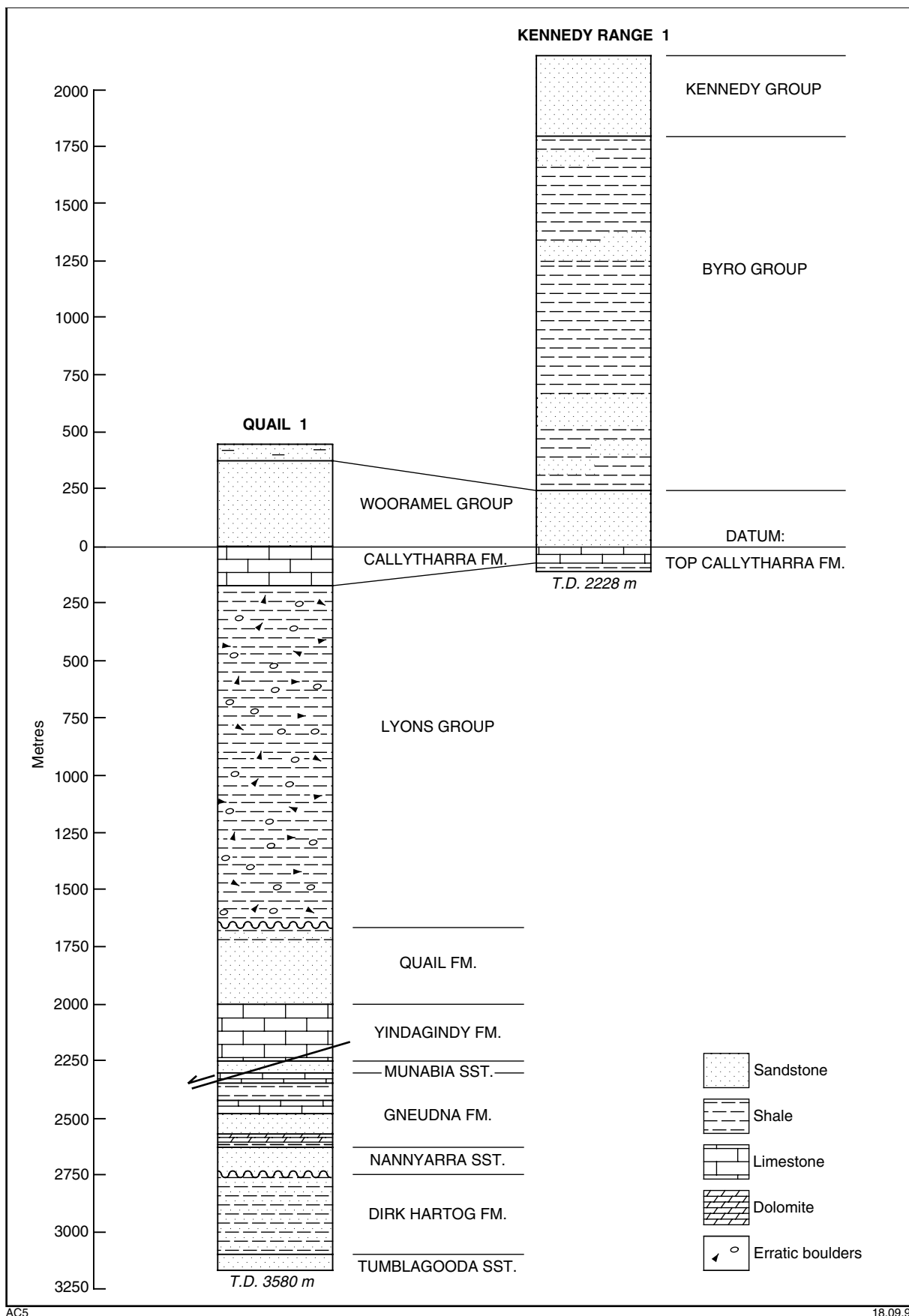
Figure 5. Stratigraphic correlation between Quail 1 and Kennedy Range 1

to lower Late Permian; and a thin Cretaceous sequence. A very thin veneer of Eocene clastic rocks is present in places. Figure 5 illustrates the lithostratigraphy of the two main cycles in the subsurface of the Merlinleigh Sub-basin. The original stratigraphic definition of the sequence in Quail 1 has been substantially revised and this Report follows the definition of Bentley (1988), with the exception of the Yindagindy Formation, whose definition is based on the Visean (Early Carboniferous) age demonstrated by Nicoll and Gorter (1995). The penetrated stratigraphy, when compared with the sequence regionally present, and the interpreted structural setting, suggest that a normal fault was encountered by the well between the Yindagindy Formation and the Munabia Sandstone, cutting out the Willaraddie Formation, the Moogaree Limestone, and possibly the Williambury Formation (Fig. 5).

The oldest Devonian unit is the shallow-marine transgressive Nannyarra Sandstone, which was deposited discontinuously over an exposed Silurian or older surface (Fig. 5). The unit consists of sandy siliciclastic rocks, with only minor siltstone or claystone. The Gneudna Formation either conformably overlies the Nannyarra Sandstone, or unconformably rests on the Precambrian basement where the Nannyarra Sandstone is absent. In the type section on the Williambury station (Hocking, 1990) the Gneudna Formation is represented by interbeds of carbonates, estimated to constitute some 40% of the sequence, and poorly exposed fine-grained clastic sedimentary rocks (Fig. 6). In Quail 1 the unit is represented by predominant limestones, with claystone interbeds. A rich fauna of brachiopods, bivalves, stromatoporoids, corals, crinoids, algae, and other fossils is present in the Gneudna Formation suggesting deposition on a warm, shallow shelf (Hocking et al., 1987). The greater thickness of terrigenous clastic material in outcrop than in Quail 1 and Wandagee 1 may reflect near-shore interfingering of clastic materials, which do not extend to the offshore areas.

Two Devonian clastic units conformably overlie the Gneudna Formation, namely the Munabia Sandstone and Willaraddie Formation, represented by sandstone and conglomerate. The two units represent a regional transition from a barrier to a fan-delta environment following deposition of the Gneudna Formation (Hocking, 1990). A further marine incursion occurred in the Early Carboniferous with the deposition of the shallow to marginal marine Moogooree Limestone. Continental clastic sedimentary rocks of the Williambury Formation locally overlie these marine deposits. The Devonian – Early Carboniferous cycle terminated with the deposition of the conformable marginal-marine clastics of the Yindagindy Formation, which is partly or fully the time-equivalent of the Quail Formation, and for which a marine-shelf setting is proposed (Hocking et al., 1987). The Willaraddie Formation and all the Early Carboniferous units are absent next to the southernmost Devonian outcrops, due at least in part to erosion in the mid-Carboniferous.
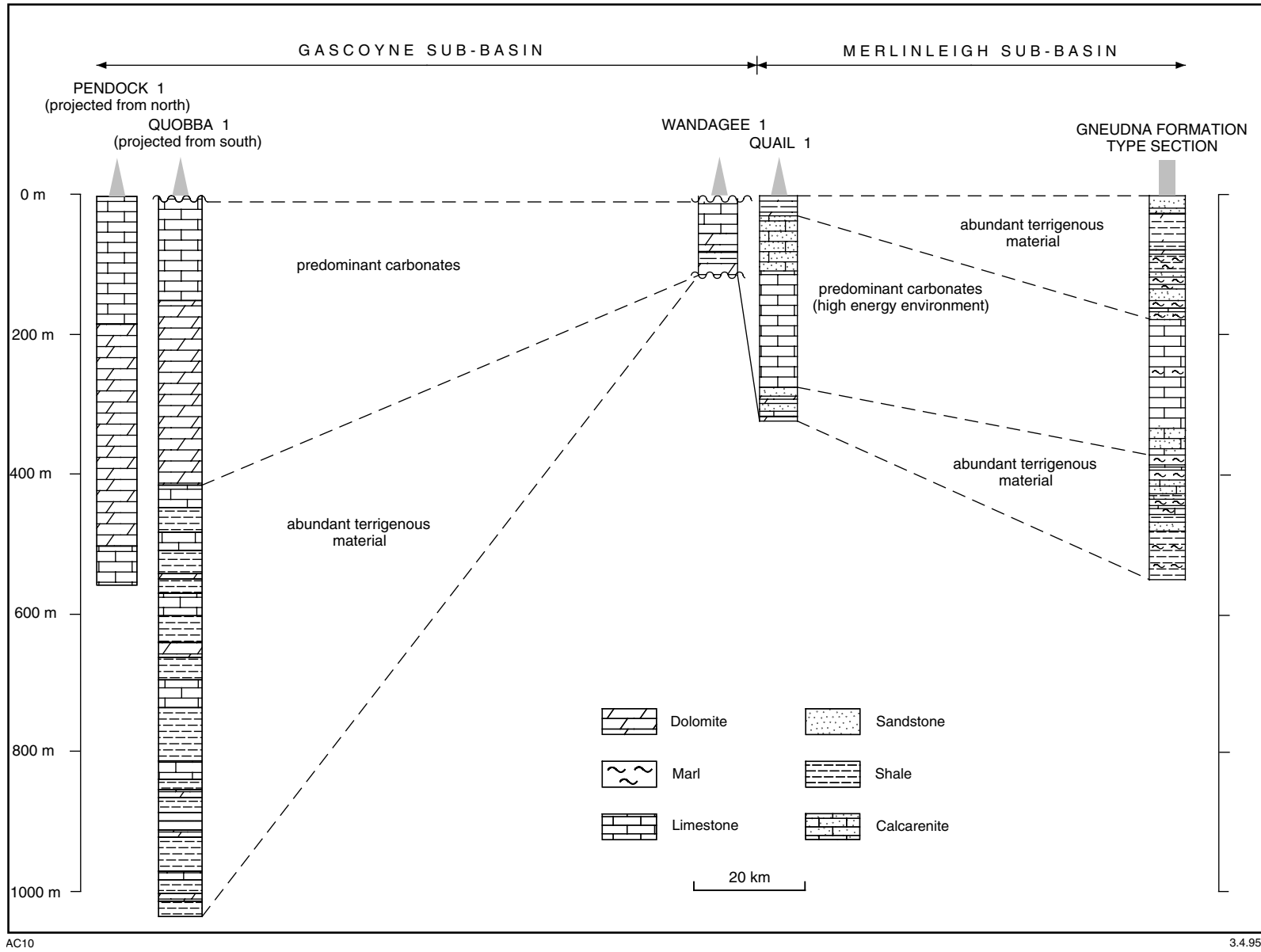
A major eustatic fall in sea level occurred at the end of the Devonian – Early Carboniferous cycle. The fall was possibly caused by a world-wide decrease in temperature and the resulting formation of extensive glaciers. The

subsequent emergence may be related to this episode, although it has also been considered that tectonic movements at this time may suggest a period of folding (Hocking et al., 1985a, 1987). Warris (1994) correlates these movements with those of the Alice Springs Orogeny.

Sedimentation resumed in the Late Carboniferous, probably coinciding with the melting of glaciers and a rise in sea level. The transgression of the Lyons Group is locally marked by a basal sandy unit: namely, the Harris Sandstone. The distribution of the Harris Sandstone appears to be controlled by basement topography; its age could be Carboniferous or Permian and its depositional environment is considered to range from fluvial to lacustrine to marine. Glacial episodes followed, interfingering with the predominantly marine, shaly sequence to form the Lyons Group. Varied erratics are typical of the lithostratigraphic unit and represent the most common outcrops. On seismic sections the Lyons Group appears well bedded, indicating a shaly sequence.

In the Merlinleigh Sub-basin, limestones of the post-glacigene Callytharra Formation conformably overlie the fine-grained clastics of the Lyons Group. In the Byro Sub-basin the shaly Carrandibby Formation has been identified at the top of the Lyons Group, underlying the Callytharra Formation. The Callytharra Formation is represented by calcareous siltstone grading upwards to very fossiliferous calcarenite, indicating a shallowing-up marine-shelf environment (Hocking et al., 1987). The upper part of the Callytharra Formation is characterized by a spectacular karst terrain over large areas. The karstification has been interpreted as the result of subaerial exposure before the deposition of the overlying Wooramel Group (Hocking et al., 1987), although the karst terrain occurs where there are no overlying sedimentary rocks. In a typical karst outcrop in the Congo syncline (Hocking, 1990), the calcareous subvertical walls of the towers delimit subhorizontal karst corridors (Hocking et al., 1987, fig. 55) whose even surfaces are filled with fine-grained alluvium. Such a flat-floored terrain is characteristic of the bottom of dolines and poljes (interior valleys). An alternative interpretation is that the karst terrain developed following the uplift of the Permian sequence and the subsequent local erosion of the post-Callytharra sedimentary rocks during the last 200 million years or so.

As indicated by seismic data, the Wooramel Group conformably overlies the Callytharra Formation, consistent with the alternative interpretation of the karst terrain. It is a siliciclastic fluvial to marine deltaic sequence (Hocking et al., 1987). The fine-grained, locally silty Cordalia Sandstone represents the basal unit of the group over a large part of the Merlinleigh Sub-basin and passes both upwards and laterally to the Moogooloo Sandstone, which was deposited directly over the Callytharra Formation where the Cordalia Sandstone is not present. The Moogooloo Sandstone is conformably overlain by the mainly fine-grained clastic Billidee Formation, which ranges from carbonaceous shale to silty sandstone to coarse-grained sandstone and pebble conglomerate. Carbonaceous shales, which are also present within the Moogooloo Sandstone, grade into black para-bituminous

GASCOYNE SUB-BASIN   MERLINLEIGH SUB-BASIN

PENDOCK 1
(projected from north)

QUOBBA 1
(projected from south)

WANDAGEE 1

QUAIL 1

GNEUDNA FORMATION
TYPE SECTION

predominant carbonates

abundant terrigenous
material

predominant carbonates
(high energy environment)

abundant terrigenous
material

abundant terrigenous
material

Dolomite

Sandstone

Marl

Shale

Limestone

Calcarenite

20 km

AC10

3.4.95

Figure 6. Devonian Gneudna Formation sequences within the onshore Carnarvon Basin. The illustrated sequences virtually occupy the same position within the Devonian epeiric sea, parallel to its southern border, with the possible exception of the Pendock 1 section

coal seams. A high total organic carbon (TOC) content reflects the abundance of coal in the unit. The Billidee Formation also contains one or more bioclastic limestone intervals with restricted areal distribution: the Jimba Jimba Calcarenite Member, and facies equivalents thereof. Within the Byro Sub-basin the Billidee Formation is laterally substituted by the coarser-grained sands of the Keogh Formation. This probably reflects proximity to the basin margin.

The Byro Group conformably overlies the Wooramel Group. It comprises eight discrete lithostratigraphic units in which six facies have been differentiated, ranging from black shale to cross-stratified sands. The group represents a siliciclastic, storm-dominated marine-shelf sequence.

The Kennedy Group conformably overlies the Byro Group and contains similar siliciclastic sedimentary rocks indicative of a marine-shelf environment. The Kennedy Group contains three formations that were traditionally considered as a conformable sequence (Condon, 1967; Hocking et al., 1987). Following further work in 1992, Hocking (pers. comm.) now considers that a significant unconformity separates the lower formation in the Kennedy Group from the two overlying formations. Thus, the lower formation, the Coolkilya Sandstone, could be placed in the Byro Group, and the two upper formations in a diminished Kennedy Group. The palaeontological data are poor and inconclusive, but a Late Permian age is preferred for the two younger units. R. M. Hocking and A. J. Mory (pers. comm., 1994) prefer to correlate the amended Byro Group with the Carynginia Formation of the Perth Basin, and the amended Kennedy Group with the Wagina Sandstone.

The entire Permian sequence of the Merlinleigh and Byro Sub-basins is correlatable with the Permian sequence in the Perth Basin (Fig. 2). The similar coal-forming environment of the coeval Irwin River Coal Measures (Perth Basin) and Wooramel Group (Carnarvon Basin) is noteworthy for its similar source-rock potential.

Triassic and Jurassic sedimentary rocks are absent from the area of study. It is considered that the Kennedy Group virtually filled up the Permian Merlinleigh rift basin. Only minor epeirogenic movements occurred until the post-breakup, regional marine transgression of the Early Neocomian affected the region.

The Cretaceous cycle is represented by the Winning Group, which onshore is very thin. In the Kennedy Range area of the Merlinleigh Sub-basin the Winning Group is represented by the basal diachronous transgressive Birdrong Sandstone, the conformably overlying silty Muderong Shale, and the superimposed Windalia Radiolarite. The entire thickness of the Winning Group in the Merlinleigh Sub-basin does not exceed 100 m, allowing subcrop information to be easily obtained from shallow coreholes (Fig. 7).

A final episode of marine transgression over the area occurred during the Middle–Late Eocene, when the coarse-grained Merlinleigh Sandstone and its time and facies equivalent, the Pindilya Formation, were deposited. In the sub-basins to the west the Tertiary series lies conformably over the Mesozoic series, indicating that, onshore, only epeirogenic movements occurred between the deposition of the Cretaceous and Eocene units. The Eocene units indicate a near-shore to coastal setting and on average are 10 m thick. The Eocene sedimentary rocks overstep Cretaceous sedimentary rocks to the east and are therefore locally unconformably transgressive on Permian sedimentary rocks, as can be observed along the eastern margin of the Kennedy Range. The Merlinleigh Sandstone almost conformably overlies the subhorizontal Kennedy Group over large areas indicating that only minor erosion took place before the Eocene transgression. Notwithstanding its limited thickness, the Eocene sequence is critical in establishing the structural history of the area, since it offers a direct indication of the age of the last tectonism, which post-dates its deposition.

History of petroleum exploration

Oil companies first showed an interest in the Merlinleigh Sub-basin in the 1930s, when hydrocarbon shows were encountered during the drilling of shallow water wells in the northern part of the region (Condit, 1935). However, the only oil exploration activities at the time were reconnaissance geological traverses carried out by Oil Search.

In the late 1950s, the Bureau of Mineral Resources (BMR) mapped large portions of the Merlinleigh and Byro Sub-basins and drilled several stratigraphic holes, namely BMR 6, 7, 8, and 9 (Fig. 8). Mercer (1967) reported that BMR 9, located in a synclinal area within the Byro Sub-basin, encountered 'suspected oily water' in the Lyons Formation, which was not properly evaluated.

The first serious oil exploration program in the Merlinleigh Sub-basin was carried out by West Australian Petroleum (WAPET) in the 1950s and 1960s, following the euphoria of the Rough Range discovery. Reconnaissance geological and geophysical surveys were followed in 1961–62 by the recording of 120 km of seismic profiles, for which dynamite was used as a source, and by the drilling of three coreholes in the Wandagee area. The results of one of the shallow coreholes led WAPET to drill a deeper well, Wandagee 1. Although the well was located on a poorly controlled positive gravity anomaly (Martin, 1962), it was defined as a stratigraphic hole because no structural closure was identified. It provided invaluable information because it confirmed that below the thin Cretaceous veneer a Devonian–Silurian, and possibly older, sequence is present in the area. The well encountered some gas shows in the Tumblagooda Sandstone, before terminating in that formation at 1074 m.

Subsequently, WAPET drilled two deep oil-exploration wells on surface structures: Quail 1 in 1963 and Kennedy Range 1 in 1966. Some poor seismic control aided the location of Quail 1, whereas the location of Kennedy Range 1 was supported by five coreholes, Merlinleigh 1 to 5 (Fig. 9). Two short seismic surveys
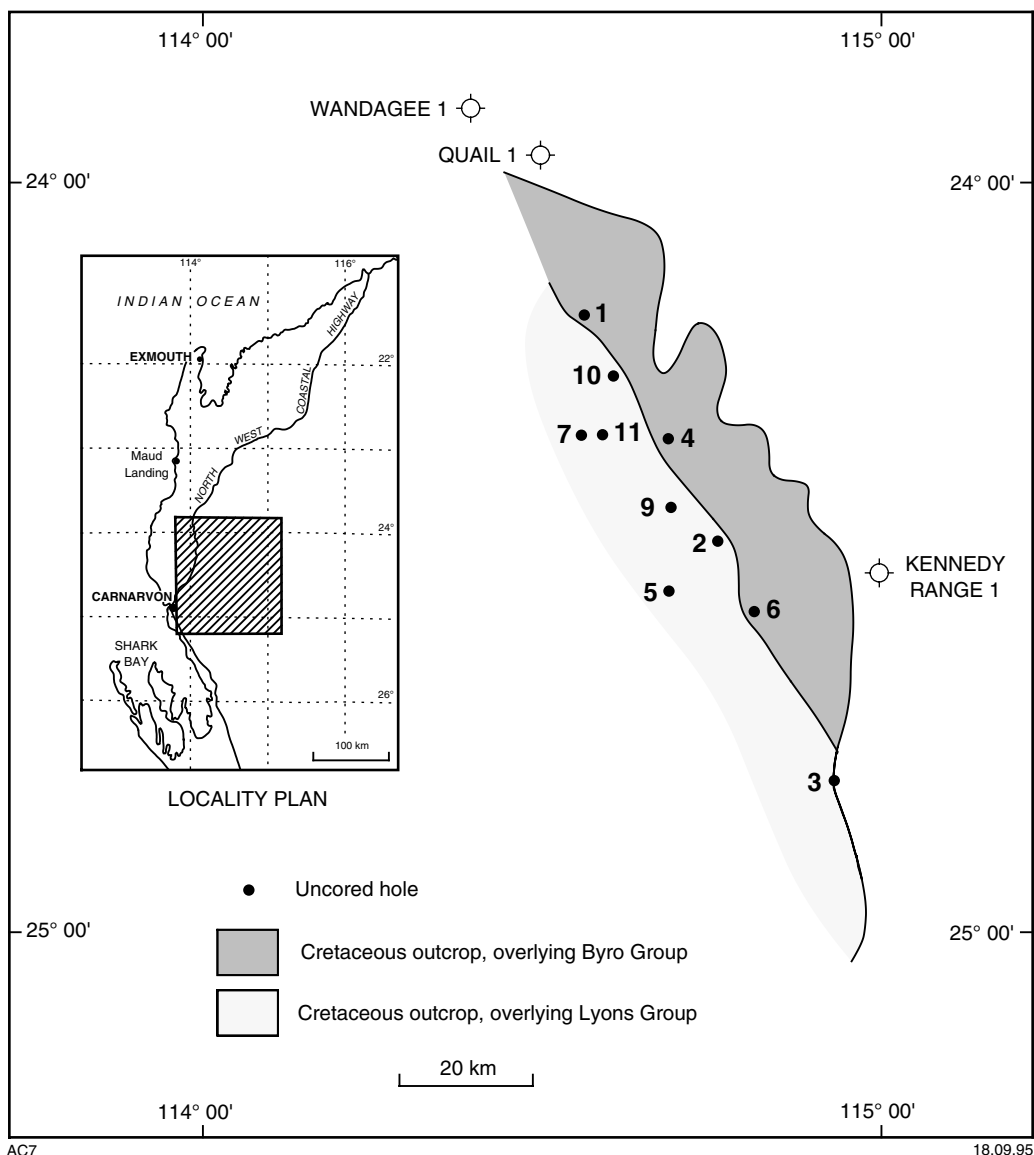
Figure 7. Possible westwards extent of the Byro Group underneath a thin veneer of Cretaceous sedimentary rocks. Interpreted from Lavering (1983b)

carried out in the Kennedy Range area in 1965 and 1966 provided only unreliable data due to the thick weathered section present. Both oil exploration wells were dry. Figure 10 illustrates the severely faulted section drilled by Quail 1, whereas Figure 11 shows the setting of the Kennedy Range structure.

Hartogen Exploration subsequently took up acreage over the Merlinleigh Sub-basin, but limited their activities to the drilling of three stratigraphic holes in 1972: Moogooree 1, Moogooree 2, and Bidjemia 1. The last serious petroleum exploration campaign was carried out in the sub-basin by ESSO in 1982–84. As illustrated by Percival and Cooney (1985), ESSO drilled eleven stratigraphic holes for a total of 1417 m, recorded 2188 km of seismic lines, and tested two features by drilling Burna 1 (Percival, 1985) and Gascoyne 1 (Greenwood, 1985). Both

exploration wells were dry, allegedly because of lack of seal.

A different approach to oil exploration was followed in 1991 by Pan Pacific Petroleum NL, at the time controlling Sealot, which carried out a geochemistry survey in the northern part of the Merlinleigh Sub-basin (Fugro Douglas Geochemistry Pty Ltd, 1991). The main result of the survey confirmed that hydrocarbons are still being generated by Permian sedimentary rocks in the area or are migrating from existing accumulations. Two clusters of geochemical anomalies were identified: one within the intensely faulted western margin, probably related to shallow Permian source rocks, and the second within the eastern margin of the basin, probably related to subcropping Devonian source rocks (Figs 12 and 13). The former cluster of anomalies presents
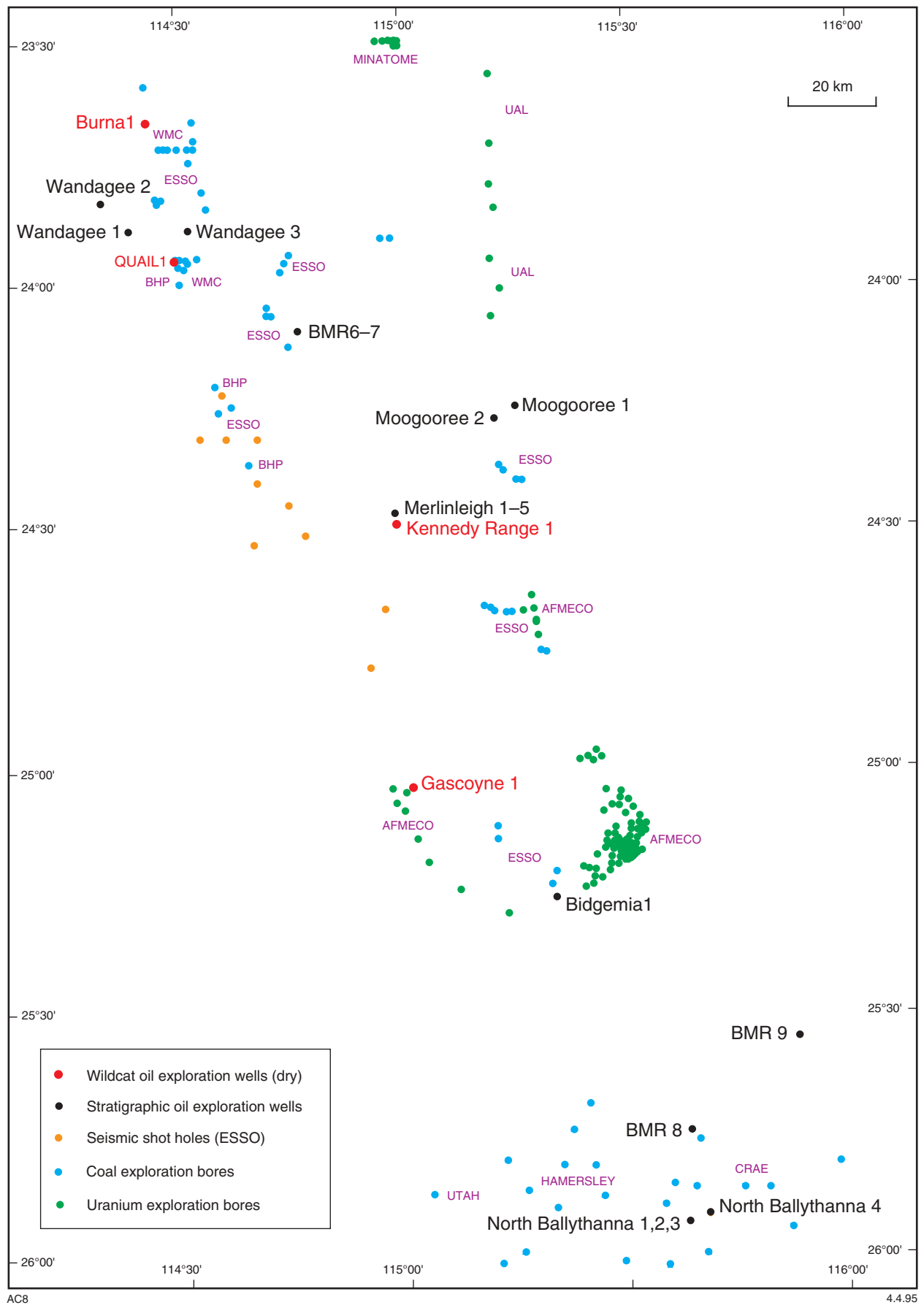
Figure 8. Well-location map for the Merlinleigh and Byro Sub-basins

115°00'

No. 5
⬦
+448'

Qs

No. 2
⬦
+519'

Pkb

Klb

Klb

No. 4
⬦
+707'

No. 3
⬦
+412'

Qs

Klb

Qs

KENNEDY RANGE 1
⬦
+753'

24°30'

-200

-100

0

Pkm

Klb

+100

+200

+300

+400

+600

+700

Pkm

+500

Pkb

N

1 km

⬦
No. 3   Merlinleigh coreholes

| Qs | Quaternary sand | | Pkb | Binthalya Formation |
| Klb | Birdrong Formation | | Pkm | Binthalya Formation (Mungadan Sandstone Member) |
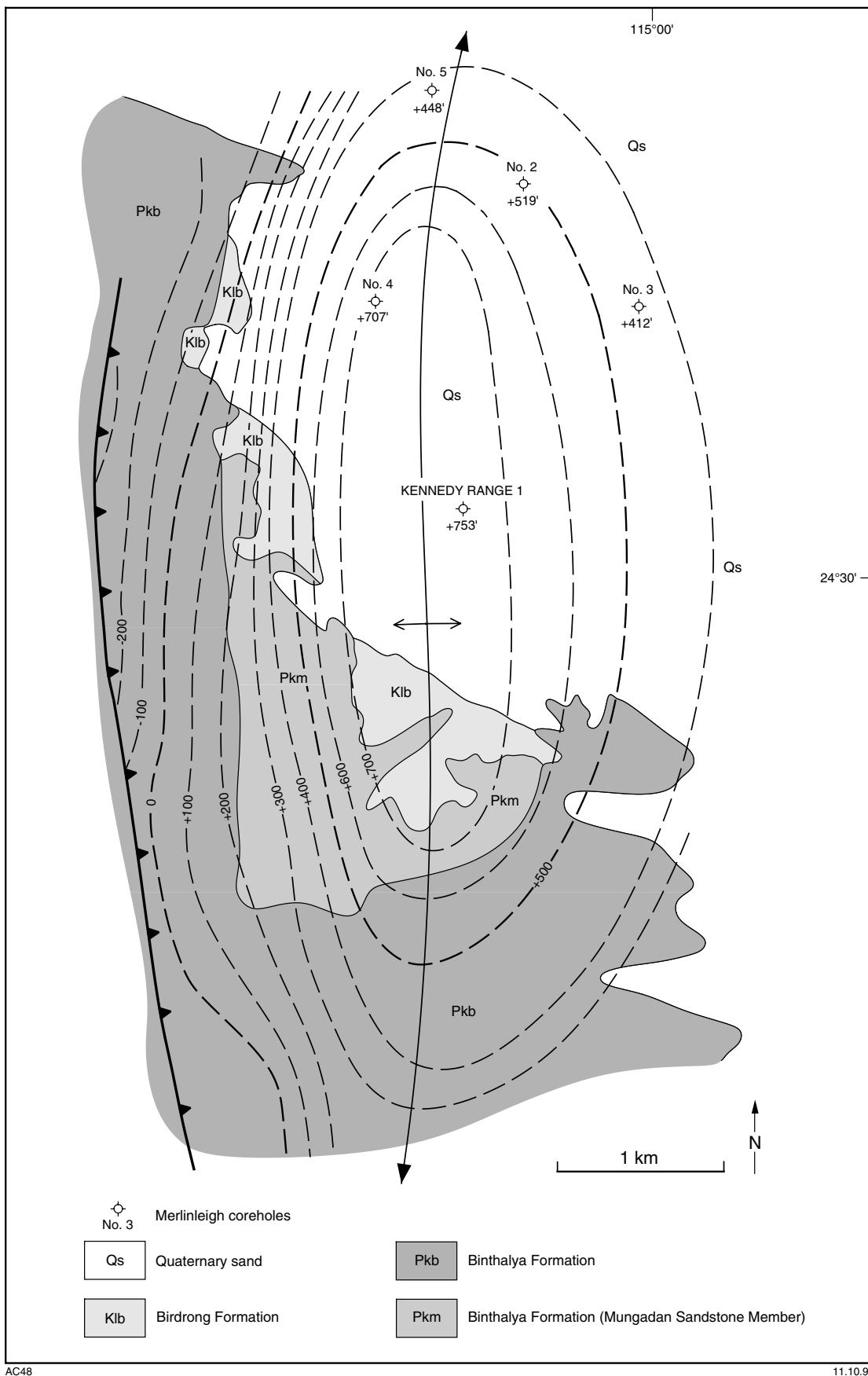
Figure 9.   Kennedy Range 1 surface anticline (after Lehmann, 1967). The well was located on the same position as Merlinleigh 1
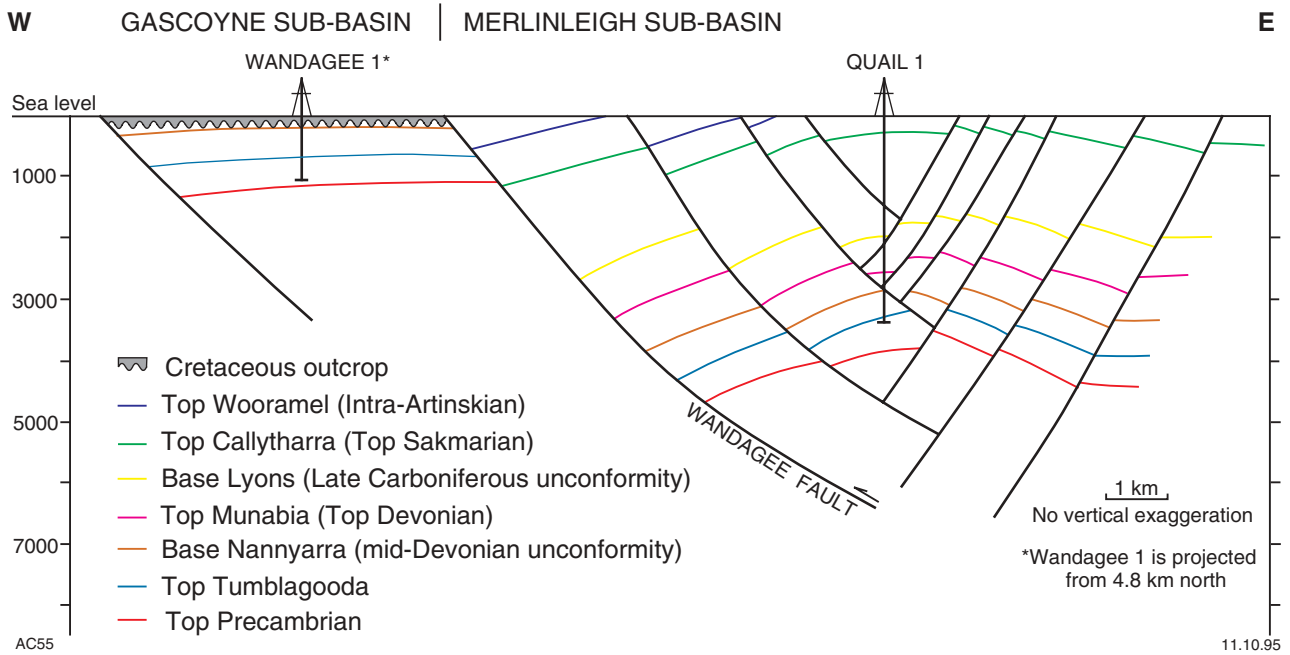
Figure 10. Boundary between the Gascoyne and Merlinleigh Sub-basins, Carnarvon Basin. Structural section across the Quail anticline, showing both Wandagee 1 and Quail 1. Interpretation from seismic lines ESSO K82A-105 and WAPET B72-2L (after Iasky et al., in prep.)
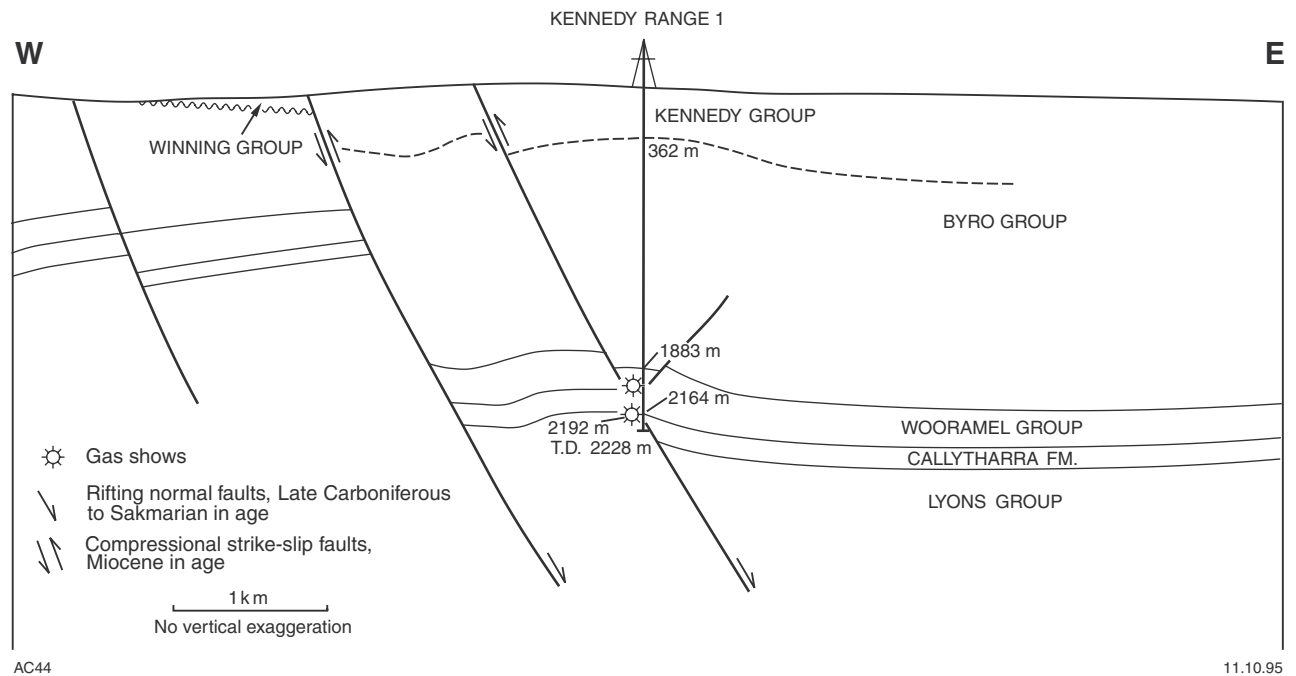
Figure 11. Structural section across the Kennedy Range structure, Merlinleigh Sub-basin, interpreted from surface geology, Merlinleigh coreholes 1 to 5 (Fig. 9), and Kennedy Range 1 core data
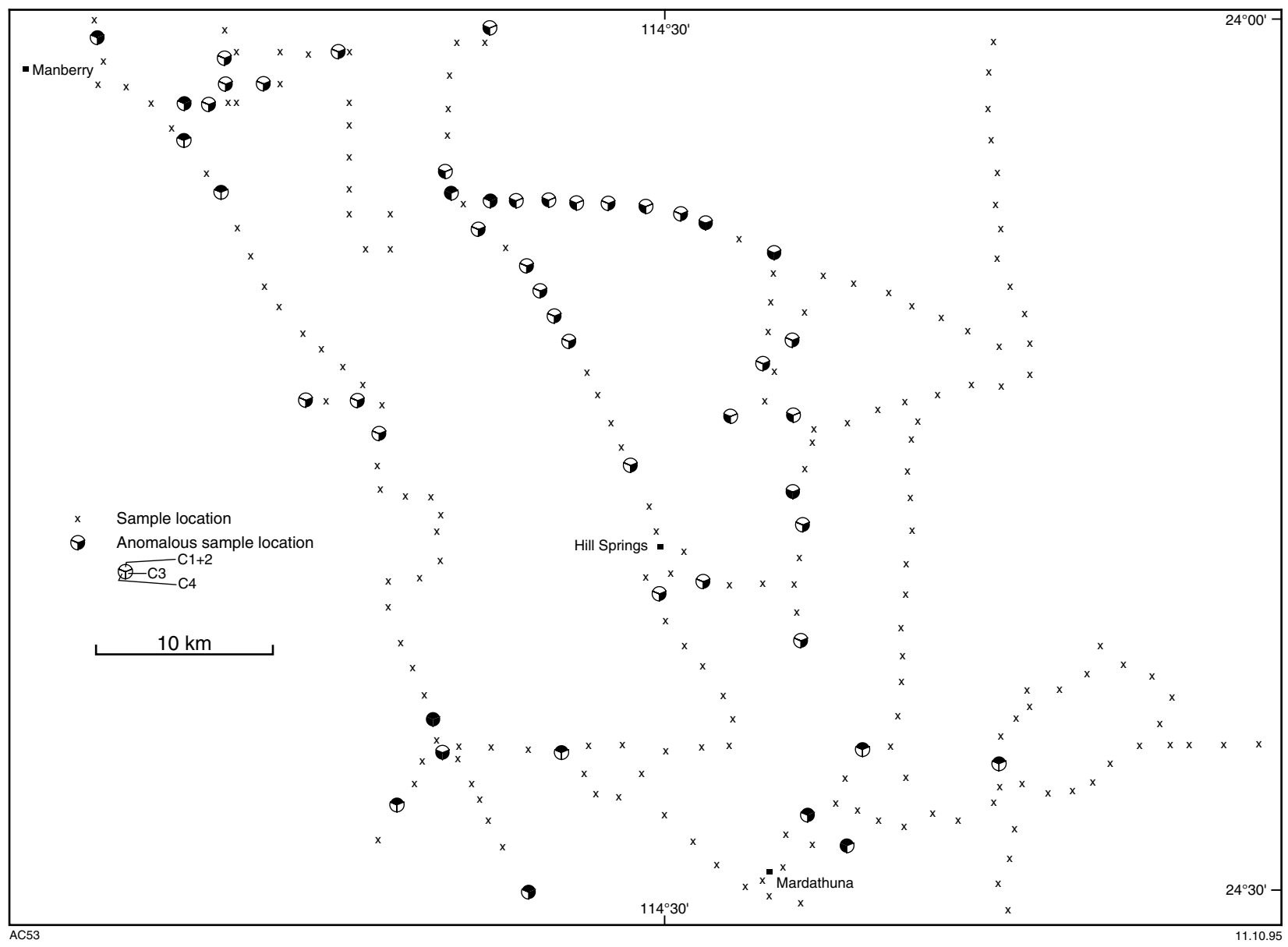
Figure 12. Merlinleigh Sub-basin geochemical survey (Fugro Douglas Geochemistry Pty Ltd, 1991): western section

24°00'

114°30'

Manberry

Sample location

Anomalous sample location

C1+2

C3

C4

10 km

Hill Springs

Mardathuna

24°30'

114°30'

AC53

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Figure 13. Merlinleigh Sub-basin geochemical survey (Fugro Douglas Geochemistry Pty Ltd, 1991): eastern section

a higher concentration of methane and ethane, which are considered to have moved upwards along the numerous fault planes.

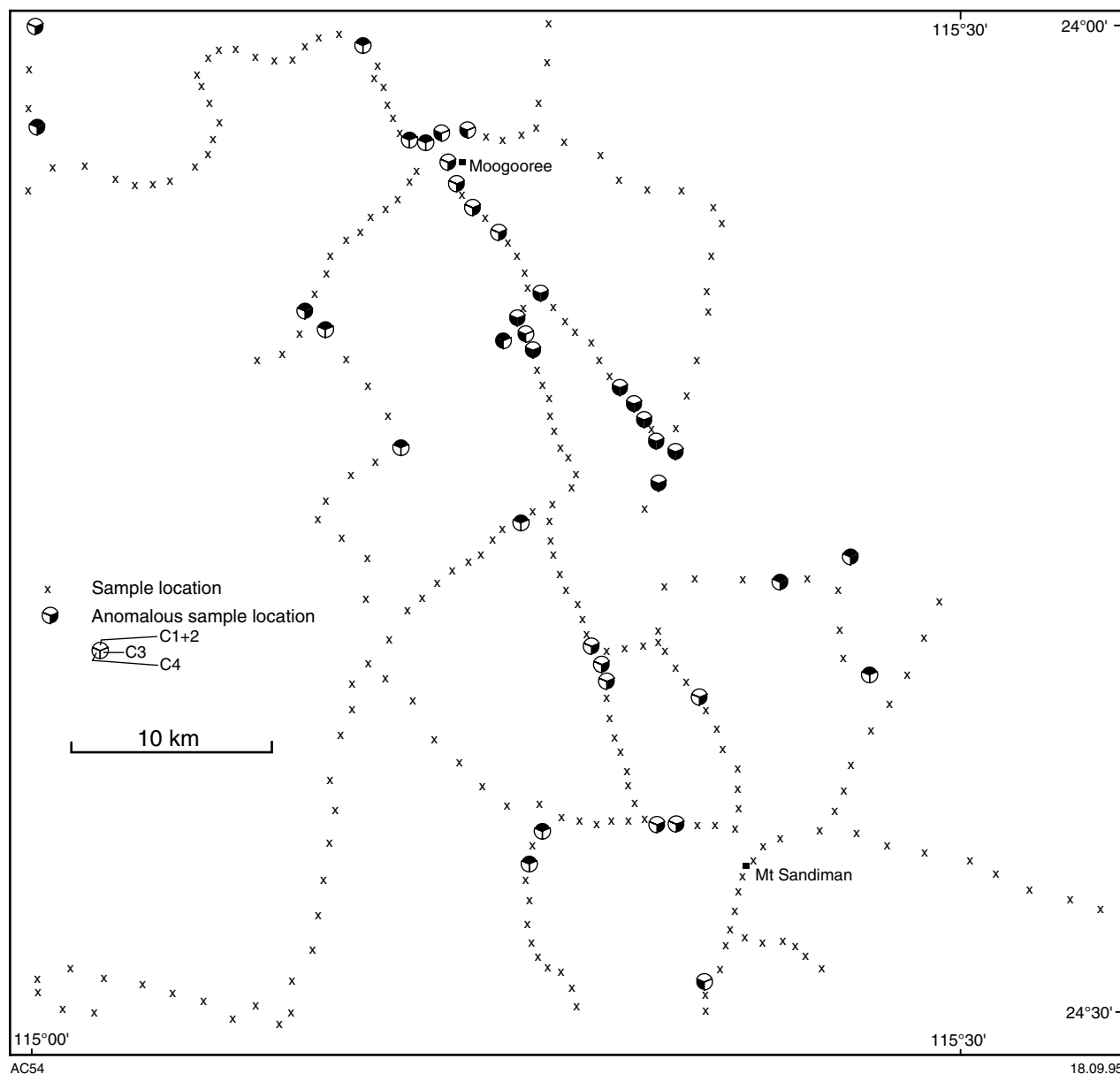More recent exploration activity in the Merlinleigh Sub-basin has focused on source-rock studies. These studies were carried out by Mitchell (1992) on behalf of Stirling Resources NL, and by Geotechnical Services (1994) on behalf of Sealot, a subsidiary of Kiwi International Resources NL. Reprocessing of seismic data and Landsat studies (Russell, 1992, 1993) have also been carried out by Sealot. The interpretation of the re-processed seismic data (Carnarvon Petroleum NL, 1993) did not lead to the drilling of any wells.

Exploration activity in the Byro Sub-basin has been limited to seismic surveys in the northernmost part of the

area carried out by CONOCO in 1965 and 1966, and by Eagle Corporation in 1982. Terril (1982) concluded that the surveyed Ballythanna anticline was poorly documented at depth and open to the south.

Coreholes drilled for coal or other minerals (Fig. 8) provided additional stratigraphic and geochemical information. In 1973–74, Uranerz drilled 20 coreholes on Williambury station to test the potential of the Devonian sequence for uranium. In 1975, BHP drilled seven coreholes for the evaluation of a Permian coal seam in the general area of Wandagee. In 1978 and 1980, AFMECO drilled 93 holes during uranium exploration in the southern part of the Merlinleigh Sub-basin. In 1980–81, ESSO drilled 67 wells for oil-shale exploration in various parts of the Merlinleigh Sub-basin: the geochemical results from these wells prompted the ESSO oil-exploration activities

in the area. In 1984, Western Mining Corporation (WMC) drilled 20 holes for coal exploration in the northwestern part of the Merlinleigh Sub-basin.

Coal exploration holes were also drilled in the northern part of the Byro Sub-basin by CRAE (31 holes in 1979–80), Utah (25 holes in 1980–81), and Hamersley (27 holes in 1981), all across the Permian sequence.

Structural setting

Information on the structural setting of the region is provided by outcrop, gravity, magnetic, seismic, and well data.

The interpreted pre-Cretaceous geology of Hocking et al. (1987, plate 2), supplemented by the 1:250 000 geological maps of KENNEDY RANGE* (Hocking et al., 1985a), WINNING POOL – MINILYA (Hocking et al., 1985b), WOORAMEL (Denman et al., 1985), BYRO (Williams et al., 1983a), and GLENBURGH (Williams et al., 1983b), indicates that two main structural trends are present in the Merlinleigh and Byro Sub-basins. They are en echelon northerly trending faults along the western margin of the Merlinleigh Sub-basin, between 24° and 25°S, and north-northeasterly to northeasterly trending faults along its eastern margin, within its southern part, and within the Byro Sub-basin.

The gravity image (Fig. 4) of the Merlinleigh Sub-basin shows a north-northwesterly trending lineament subparallel to the surface of the Wandagee Fault, a subparallel trough to the east, and several northeasterly trending lineaments. The gravity image also illustrates that the Byro Sub-basin is characterized in its northern section by southwesterly trending lineaments, which become more southerly trending to the west and extend into the Coolcalalaya Sub-basin as lineaments trending north–south.

McWhae (1956) provided the first structural interpretation of the region, which has been superseded by the large amount of data subsequently acquired.

The WAPET map attached to the final seismic interpretation report on the Quail area (Denton and McBeath, 1963) shows an elongate north-northwesterly oriented anticline, flanked by subparallel faults (Fig. 14). The seismically interpreted westernmost fault, which has been taken to correspond to the surface of the Wandagee Fault, is also oriented north-northwest. All the faults are interpreted to be normal, and the crest of the structure is downthrown with respect to both its western and eastern segments. The faults that are orthogonal to the axis of the Quail anticline are also downthrown towards the drilled apex. The postulated southern closure of the anticline is fault dependent and the north plunging axis does not show definite closure to the south.

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* Capitalized names refer to standard map sheets.

The ESSO seismic line K82A-105, together with the WAPET line B72-2L, which was reprocessed by Western Geophysical in 1991, allow for an alternative interpretation. Figure 10, which was constructed by R. P. Iasky and is part of the ongoing GSWA review of the area, illustrates such an interpretation. The presence of several faults in Quail 1 is also supported by the dipmeter data. The Quail anticline is interpreted as a compressional feature, controlled to the west by a reverse fault and to the east by an antithetic fault. It is intersected by a series of down to the crest normal faults and can be defined as a negative-flower structure. The described structural style is suggestive of a wrench-induced anticline, similar to many structures within the Perth Basin (Crostella, 1995) and the Barrow Sub-basin (Parry and Smith, 1988; McClure et al., 1988). The stratigraphic results from Wandagee 1 and Quail 1 indicate that the major fault bounding the Quail structure to the west, namely the fault subparallel to the surface of the Wandagee Fault, separates a western province in which Cretaceous sedimentary rocks unconformably overlie Devonian rocks from an eastern province where more than 2000 m of Permian rocks are present. Furthermore, it is likely that a total of approximately 4000 m of sedimentary rocks were deposited in the area (Fig. 5).

Dipmeter data show that Kennedy Range 1 encountered steeper strata in the lowermost section than in the uppermost one. The mapped northerly trending elongated surface anticline (Fig. 9) does not correspond to the structure at depth. In outcrop, the western flank of the structure presents a more complex fault pattern than shown on KENNEDY RANGE (Hocking et al., 1985a). The main fault, the Kennedy Range Fault, is northerly trending. The elongated longitudinal axis of the structure subparallel to the bounding fault suggests the presence of a reverse fault (Tearpock and Bischke, 1991, p. 158), overthrown to the west. This is confirmed by the presence of younger strata (Cretaceous) in the section that was downthrown in the Miocene (Fig. 11).

Detailed structural information on the Merlinleigh Sub-basin is provided by ESSO's geophysical maps (Greenwood, 1984). A simplified version of the ESSO geophysical interpretation is shown in Figure 15. The eastern depositional boundary of the basin is in agreement with surface mapping, whereas the western margin in the mapped northern segment is clearly fault controlled. To the south of the Quail area, the western margin is not mapped, although sparse seismic data, scattered outcrops, and results of shallow drilling suggest that it is a depositional boundary (Fig. 7). Within the northwestern portion of the area, where Burna 1 was located, intense faulting and close contours indicate westerly directed compressional stresses. This interpretation is supported by the structure map in Percival and Cooney (1985, fig. 10).

The high concentration of northerly trending faults outcropping along the western flank of the basin are confirmed by the seismic data, whereas northeasterly trending gravity lineaments on the eastern flank and southern portion of the sub-basin are only partially supported, suggesting that they represent older tectonic
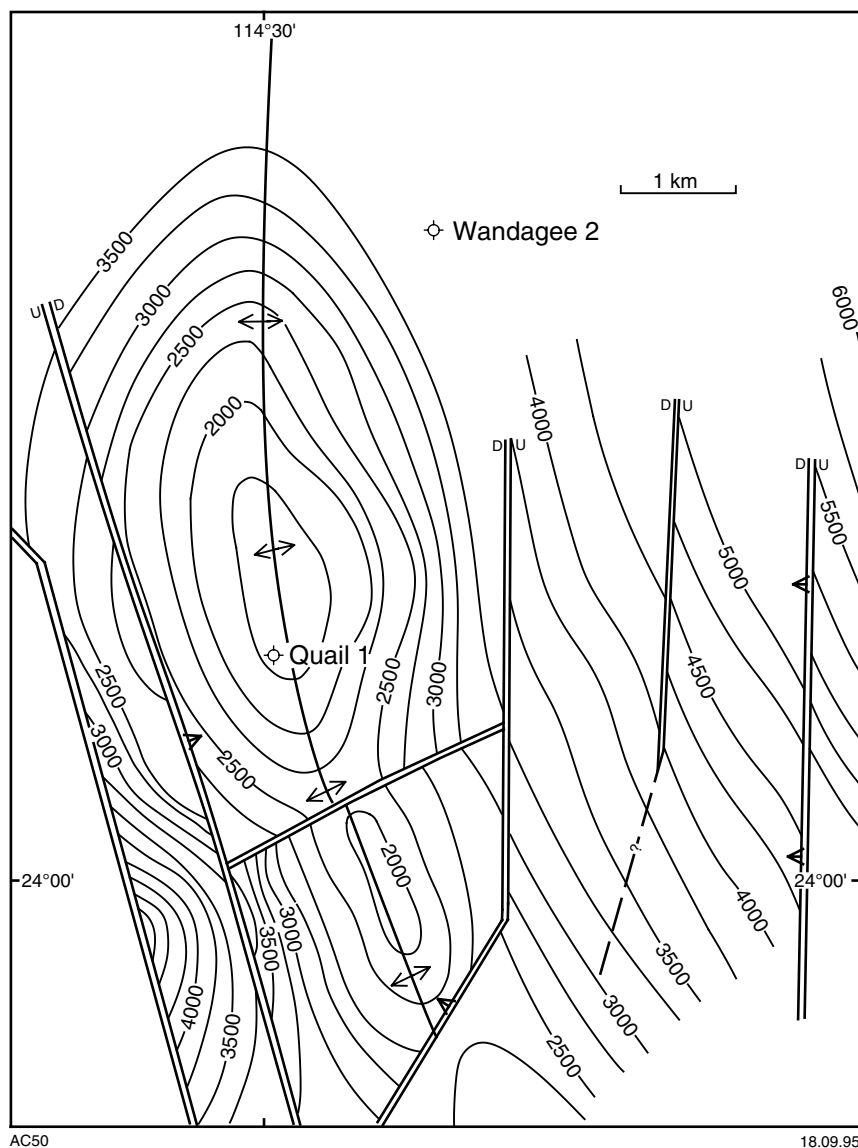
Figure 14. Quail Project: Phantom Horizon A. Seismic map (Denton and McBeath, 1963)

movements that have subsequently been rejuvenated. The en echelon attitude of the northerly trending faults between 24° and 25°S is confirmed by the seismic data: in this area there is a suggestion that compression has occurred, although it is not as accentuated as in the northern portion. This, however, may be partly due to limited seismic control. No clear structures were seismically mapped in the Merlinleigh Sub-basin, with only synclinal axes sparsely delineated in the ESSO interpretation. It may be summarized that the present configuration of the basin is clearly asymmetric with the western margin compressed to various degrees. The narrower northern portion of the sub-basin is considered to have been subjected to an east–west compressive stress. The greatest stresses have occurred in the northernmost part of the basin where it narrows and the fault pattern is divergent.

Gascoyne 1 is interpreted to have tested a segment of a fold, which is controlled by a reverse fault overthrust to the west (Fig. 16). It appears to be the structurally highest segment of the feature, although the time-structure map of the area indicates that the small Gascoyne fold depends on fault sealing to become an effective trap (Percival and Cooney, 1985).

The anticline drilled by Burna 1 (Fig. 17) is controlled by a reverse fault downthrown to the west and intersected by minor faults. This structure is consistent with the structural setting of a highly compressed belt. The well tested one segment of the fold, not necessarily the structurally highest section.

A cursory examination of the ESSO seismic lines indicates the presence of anticlinal structures (Figs 18 and
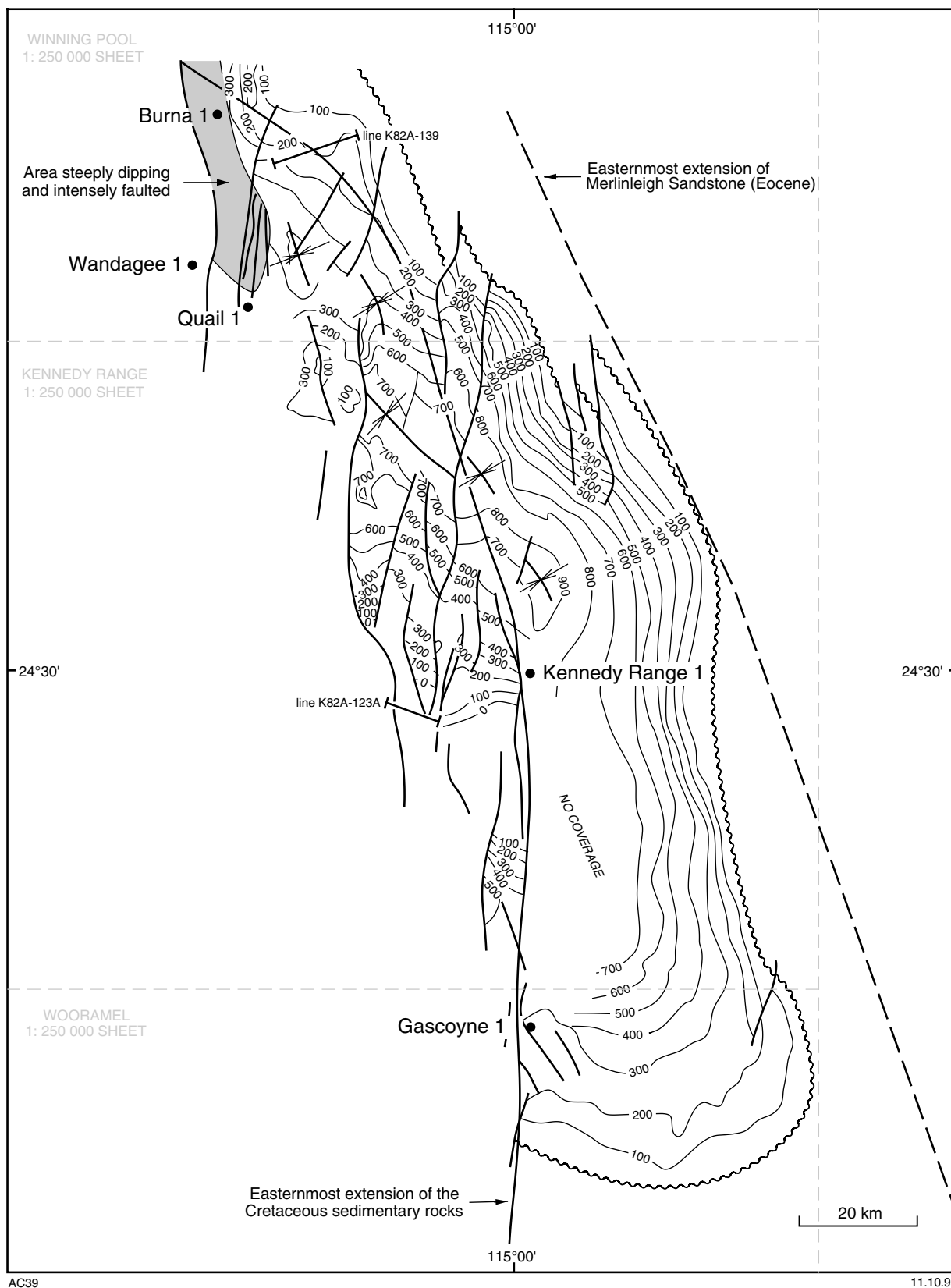
Figure 15. Seismic structural time map on top of the Wooramel Group (Early Permian) in the Merlinleigh Sub-basin (simplified from Greenwood, 1984)
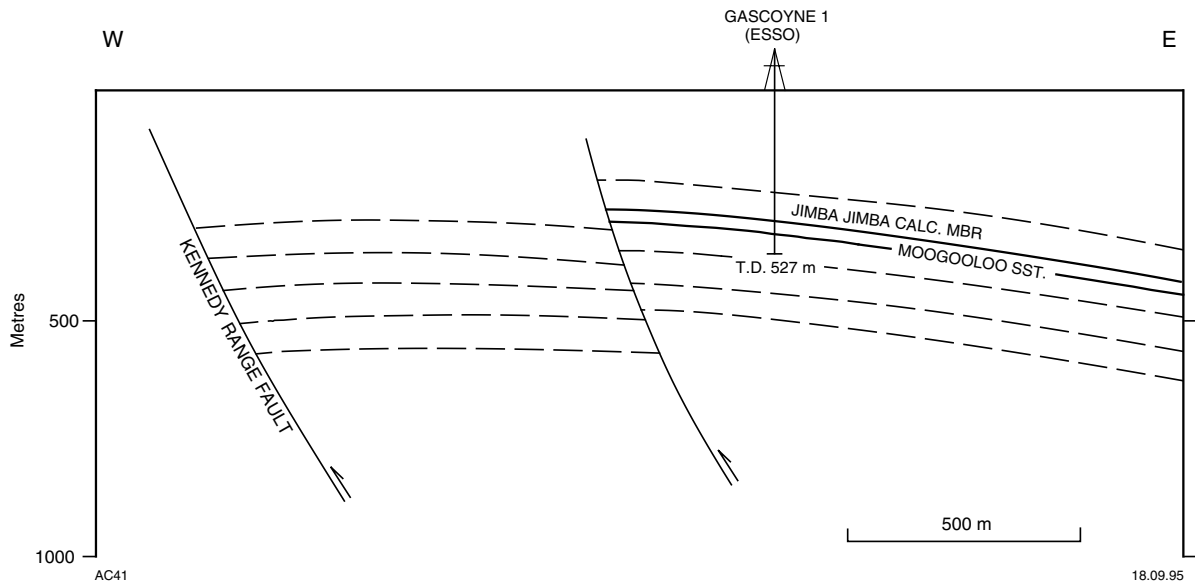
Figure 16. Structural section across the Gascoyne feature, Merlinleigh Sub-basin, interpreted from seismic line K83A-229

19), although the limited coverage does not demonstrate whether they are closed or not. In general, lack of closure to the south appears to be a critical feature.

The tectonic lineaments of the Merlinleigh and Byro Sub-basins are summarized in Figure 20. The surface lineaments are associated with either Late Permian or Miocene movements. The Late Permian trends are clearly recognizable where the Eocene sedimentary rocks appear to be undisturbed, and unconformably overlie Permian sedimentary rocks where Cretaceous sedimentary rocks are absent. The Miocene trends occur where the deformation of the rocks occurs throughout the full

Permian to Eocene sequence. These are the only movements recognizable on the surface. Gravity and magnetic lineaments are interpreted to represent the Palaeozoic grain because they predominantly sub-parallel the main downwarp of the north-northwesterly elongated basin, which dates at least from the Late Carboniferous. Similarly, northeasterly trending lineaments are probably Late Permian, since they affect Permian sedimentary rocks, but they may also represent older, rejuvenated features. An earlier age for the northeasterly lineaments is supported by their limited seismic expression, since younger tectonism masks the older movements.
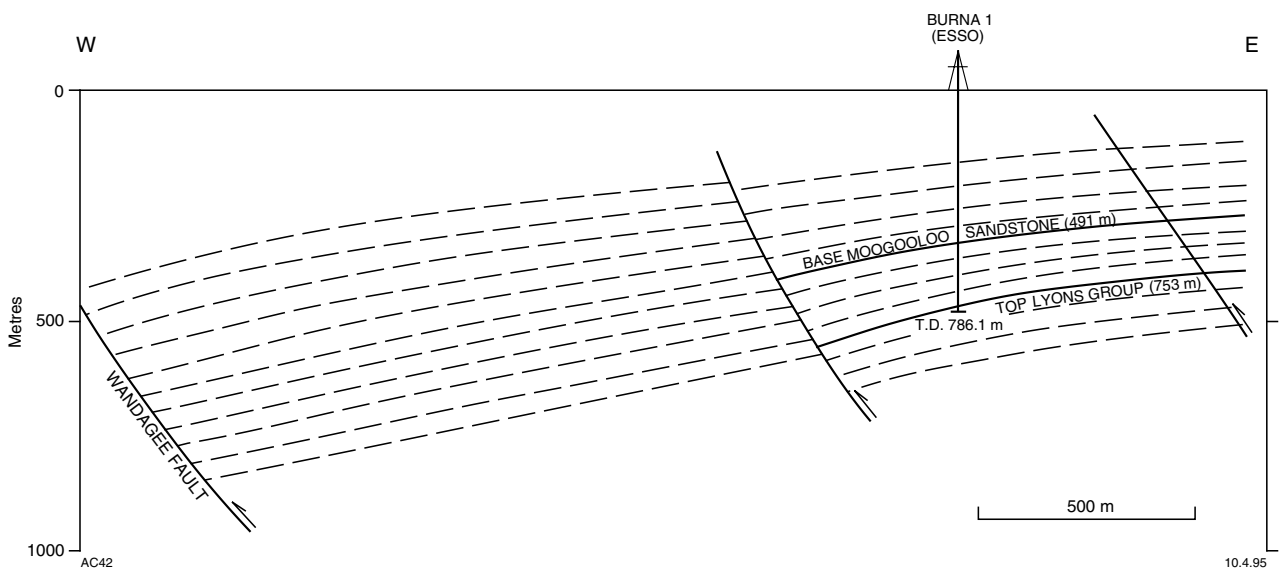
Figure 17. Structural section across the Burna feature, Merlinleigh Sub-basin, interpreted from seismic line K83A-273
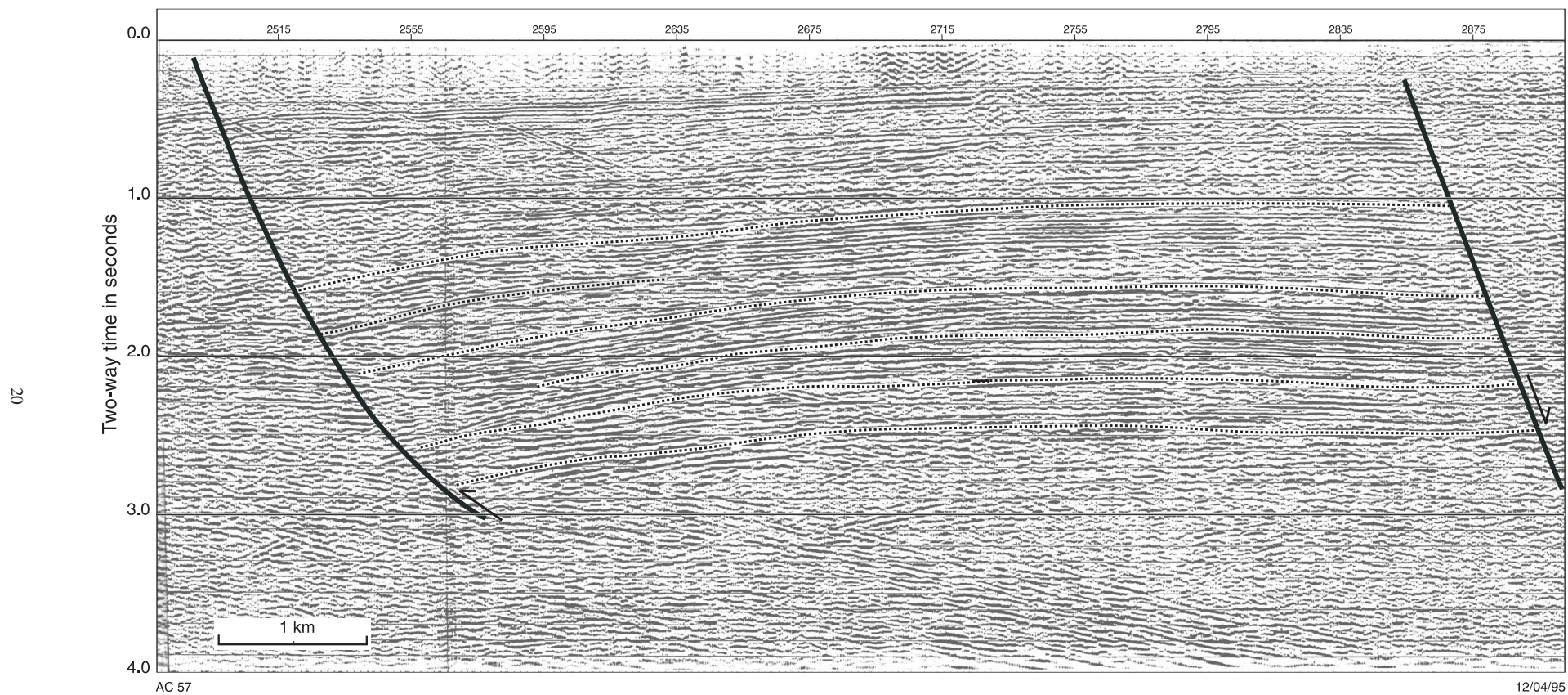
Figure 18. Seismic section K82A-139, showing a gentle anticlinal feature in the northern portion of the Merlinleigh Sub-basin. Vertical relief of up to 100 ms is present, although minor variations in thickness result in different values at different levels. The line of the section is shown in Figure 15

W   E

2070 2080 2090 2100 2110 2120 2130 2140 2150 2160 2170 2180 2190 2200 2210 2220 2230 2240 2250 2260 2270

Two-way time in seconds

0.0

0.5

1.0

1.5

1 km

AC 58   12/04/95
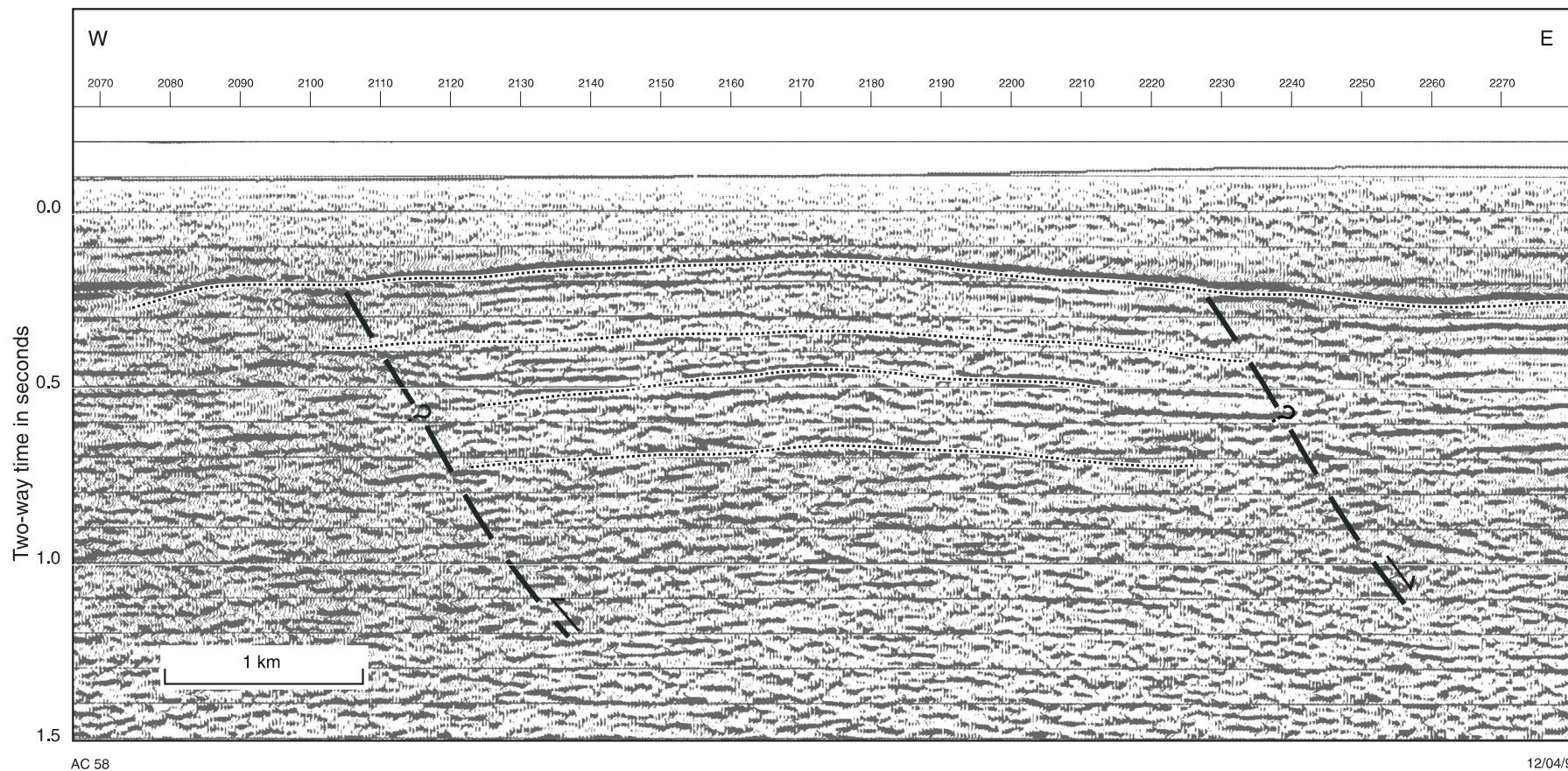
Figure 19. Seismic section K82A-123A, showing an anticline along the western belt of the Merlinleigh Sub-basin. Poor data quality below 500 ms prevents exhaustive interpretation. Corehole information (Lavering, 1983b) suggests that the Byro Group underlies a thin veneer of Cretaceous sedimentary rocks. The line of the section is shown in Figure 15
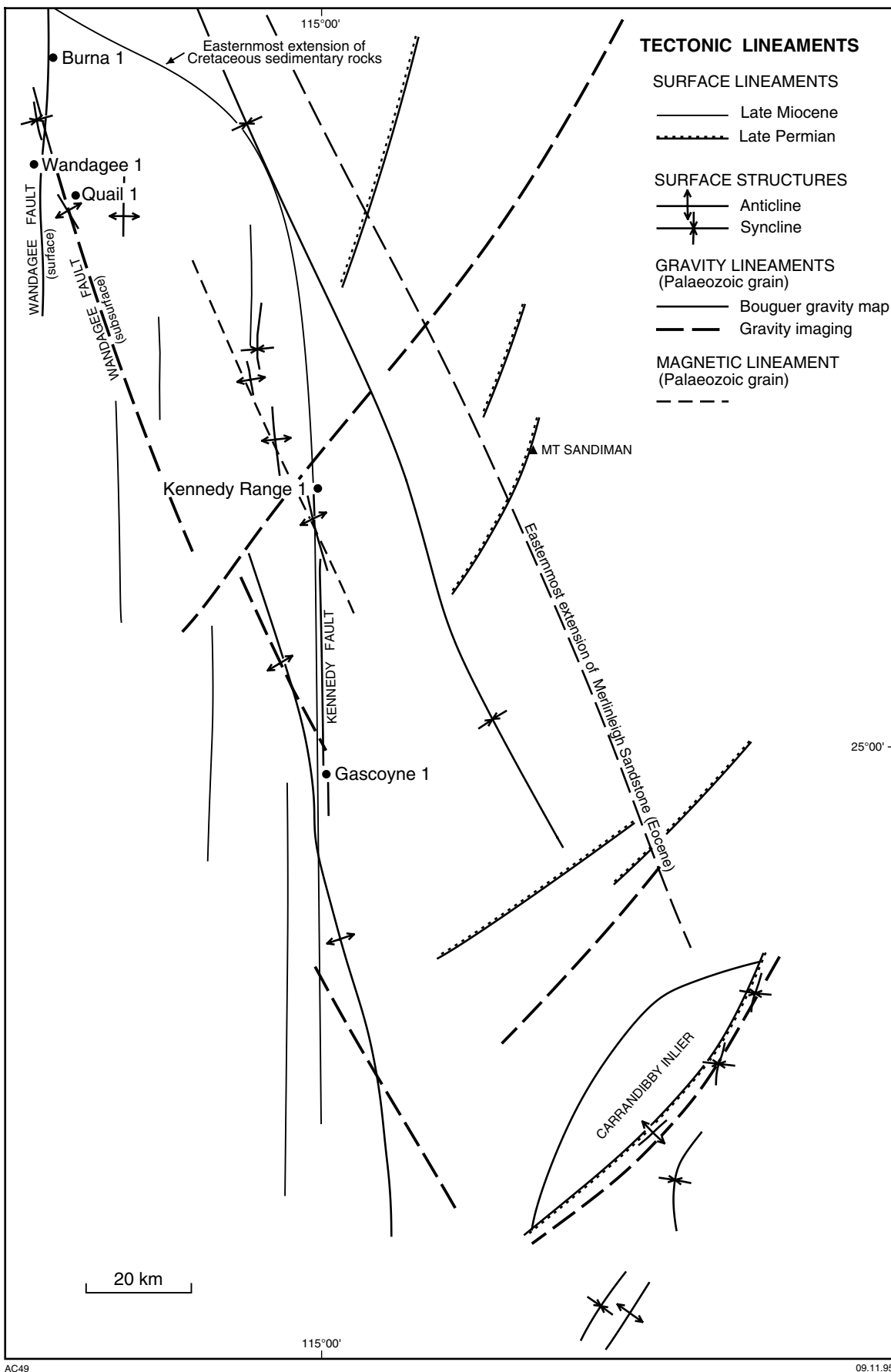
Figure 20. Tectonic lineaments, Merlinleigh and Byro Sub-basins

Basin development

The Merlinleigh Sub-basin is a Late Carboniferous to Permian downwarp, which is partly underlain by Devonian – Early Carboniferous sedimentary rocks. The pre-Late Carboniferous section is part of a larger basin extending at least over the northern part of the Gascoyne Sub-basin and probably much further afield. Condon (1965), on the basis of surface and borehole data, documents the thinning of the Devonian Gneudna Formation from north to south, and defines the approximate extent of the formation. He postulates a further possible extent of the Gneudna Formation to the south of Mount Sandiman, but this extension is considered unlikely. Northeasterly trending gravity lineaments reflecting the Palaeozoic grain are shown in Figure 4 and correspond to surface lineaments (Fig. 20) that extend into the Gascoyne Sub-basin (Hocking et al., 1987, plate 1) and offshore. These lineaments suggest that early movements may have occurred in the area in the Devonian period, or earlier, in the present day northeasterly orientation. The development of the basin was interrupted in the Late Carboniferous. Following the classification of Kingston et al. (1983), the pre-Late Carboniferous basin may be considered an 'interior sag' basin as proposed by Hocking et al. (1987). This broad, intracratonic style of basin corresponds to an infra-rift phase. This stage of basin development is not the focus of this Report.

Rifting took place at the end of the Carboniferous, with a north-northwesterly orientation, perpendicular to the direction of the horizontal extensional principal stress. It created the downwarp that was gradually filled by the Late Carboniferous – Permian sequence of the Merlinleigh Sub-basin (Figs 5 and 6). It is speculated that this sequence may be subdivided into two parts. The lower part corresponds to a period of active deformation, when the more widespread Late Carboniferous – Sakmarian rocks were deposited, whereas the upper part corresponds to a period of quiescence, when the Artinskian and younger rocks were deposited. The northern and eastern boundaries of the Merlinleigh Sub-basin are depositional in nature. To the south, sedimentation extended over the Byro Sub-basin, whereas the western margin is fault controlled. It may be said, therefore, that the main rifting episode occurred along the western margin. The Wandagee Ridge is interpreted to be a pre-Late Carboniferous feature and corresponds to the north-northwesterly trending lineaments noticeable in the gravity data (Figs 4 and 20). It is interpreted that the Late Carboniferous – Permian depositional trough extended towards the north-northwest to the North West Cape peninsula and, beneath a thick Mesozoic cover, further seawards (Fig. 21). This downwarp virtually limits the Gascoyne Platform to the north. The Wandagee Ridge extends south into an area of poor data and appears to die out. The northern part of the Byro Sub-basin developed at the same time with a northeasterly trend, indicating that the pre-Late Carboniferous trend was active in the area during the time. Anticlines, such as the Madeline Anticline, and synclines subparallel the northeasterly fault trend. In the area historically known as the Byro and Coolcalalaya Sub-basins rifting was oriented in a northerly direction.

During the Permian, the Merlinleigh and Byro Sub-basins represented a single sedimentary trough, although the Northampton–Carrandibby basement trend probably influenced the evolution of the northeasterly trending part of the Byro Sub-basin. The deposits of the two areas are in fact closely correlatable: during the time the Carrandibby Inlier was only partly exposed, if at all, because its southeastern boundary is controlled by the Madeline Fault, the major movement on which post-dates the deposition of the Permian sequence. The depth to basement map (Megallaa, 1980) suggests that up to 3000 m of Early Permian sedimentary rocks are present in the deepest part of the Byro Sub-basin, underneath a veneer of recent continental cover. The Merlinleigh, Byro, and Coolcalalaya Sub-basins represent a rift-valley phase and can be defined as an 'aborted rift' (Veevers, 1984).

The gradually regressive Kennedy Group filled the basin. Some epeirogenic movements are indicated by the angular unconformity between the gently dipping Permian Kennedy and Byro Groups and the subhorizontal Eocene Merlinleigh Sandstone, which is exposed on the eastern side of the Kennedy Range. Extensional normal faults, separating blocks of tilted sedimentary rocks, occur locally, such as in the Gooch Range. Late Permian tectonic movement occurred to the north (Warris 1994), in the Peedamullah Shelf, and a similar age can therefore be postulated for these Merlinleigh Sub-basin movements (Hocking et al., 1987).

Renewed sedimentation in the Early Neocomian reflects the thin eastern extension of the well-documented eustatic sea level rise, and only a thin succession (Winning Group) was deposited. The Winning Group represents the basal transgression of an open-marine basin, at the western margin of the Australian continent. The Eocene deposition is again the extreme edge of a major transgression.

A major tectonic event occurred along the western margin of the basin after deposition of the Eocene Merlinleigh Sandstone. All northerly trending lineaments cut Permian, Mesozoic, and Tertiary rocks. The faults are subparallel and en echelon, as shown schematically in Figures 15 and 20 and in detail on the relevant GSWA geological maps (Hocking et al., 1985a,b; Denman et al., 1985). Figure 22 shows the fault plane in the area of Twin Bores: Cretaceous sedimentary rocks proximal to the fault plane are intensely folded and reach dips of 70°. The line of the faults is quite straight, indicating a near-vertical fault plane. Where it outcrops the fault can be followed for kilometres, and the deformation of the Cretaceous and Eocene sedimentary rocks is always comparable to that of the Permian sedimentary rocks. Gentle anticlinal and synclinal folds accompany the faulting, as in the areas near Tucker Box Spring (Fig. 23), Gum Tree Springs, and southwards to the Gascoyne River. The axis of the positive features in these areas appear orientated at approximately 30° to the controlling fault. Compressional stresses are indicated by the geophysical data (Figs 7, 10, and 11). The elongated en echelon fault trend, the resulting folds, and the indicated stresses are probably the result of strike-slip movements, as suggested by Hocking et al. (1985a). Although the vertical throw is not substantial, the
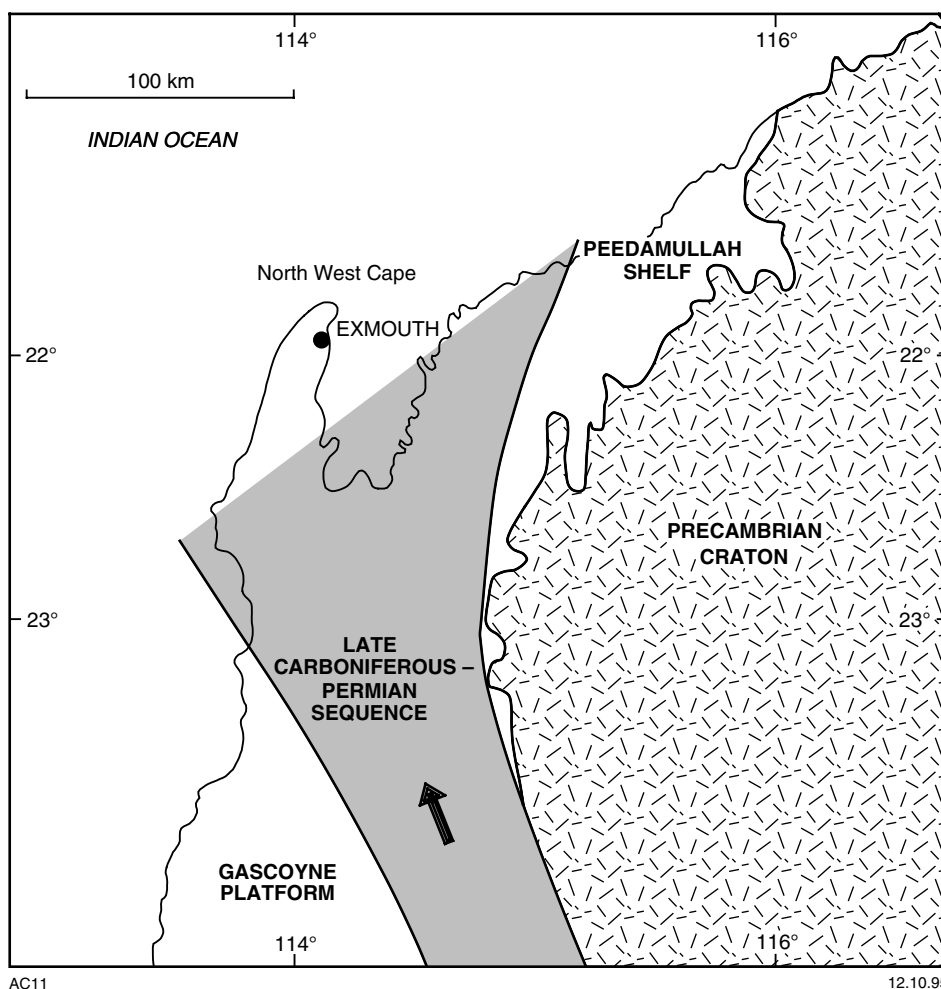
Figure 21. Late Carboniferous – Permian sedimentary rocks beneath Mesozoic cover to the west of the Merlinleigh Sub-basin outcrops. The arrow indicates the direction of deepening of the basin

horizontal throw is thought to be greater, although not measurable.

In the literature, Tertiary movements are not considered to be too important, and only a minor 'rejuvenation' is attributed to them. In effect, the only measurable substantial vertical throw is that indicated in Wandagee 1 and Quail 1. The entire Kennedy Range Fault System is represented by a series of offset en echelon faults, all of which have a minor vertical throw and which step down into the Merlinleigh Sub-basin. It is proposed that the pre-Late Carboniferous north-northwesterly trending major fault described above represents an area of weakness along which younger northerly trending strike-slip movements developed, although the pre-existing pattern was not followed exactly. It is worth noting that following Dennison et al. (1962), a possible interpretation of the gravity data acquired in the Wandagee–Quail area indicates a 'basement' ridge of early structural origin subsequently faulted by the northerly trending Wandagee Fault. The Bouguer gravity map attached to Martin's (1962) report clearly indicates a north-northwesterly trend for such a feature. The rift-related tensional down to the basin Palaeozoic tectonism is overprinted by strike-slip

Tertiary tectonism, with shortening of the western part of the Merlinleigh Sub-basin.

Tertiary movements along pre-existing zones of weakness occurred along both the eastern and western margins of the stable Gascoyne Platform. These movements produced asymmetric folds in both the Merlinleigh Sub-basin and the Quobba – Cape Range area, with the former showing steeper western limbs and the latter steeper eastern limbs, indicating that the stresses were directed towards the Gascoyne Platform. On the west, the belt stretches from the Quobba 1 trend (Blake et al., 1984; Canada Northwest Australia, 1984) to the North West Cape (Hocking et al., 1987, plate 1). Both the North West Cape and the Merlinleigh anticlines plunge to the north, whereas the southerly dip is poorly defined.

The Merlinleigh Sub-basin is bounded to the west by the Palaeozoic Wandagee Fault and its southern extension (Fig. 20), whereas the Quobba – Cape Range area is bounded to the east by the Giralia Fault. To the east of the Wandagee Fault, incompetent Late Carboniferous – Permian sedimentary rocks are juxtaposed against the competent pre-Late Carboniferous rocks, whereas in the

Quobba – Cape Range area the same competent rocks are juxtaposed against Mesozoic–Tertiary sedimentary rocks to the west. The tectonic stresses are more intense to the west of the Rough Range Fault trend, where the thick and plastic Mesozoic–Tertiary sedimentary rocks of the Exmouth Sub-basin were deposited, although the stresses also extended eastwards within the Gascoyne Sub-basin to the Giralia Fault. A tectonic–stratigraphic synthesis of the Cape Range area has been discussed and documented by Malcolm et al. (1991) who related the Carnarvon Basin Miocene tectonic events to the collision of the Australian continental margin with the Indonesian arc. Although the Miocene age of the movements supports the correlation of the two events, it is notable that compressional movements occurred along the western margin of Australia, particularly along the western and eastern flanks of the northern Gascoyne Sub-basin. Furthermore, tectonic movements in the area occurred before the mentioned collision, as Cretaceous and Eocene sedimentary rocks lie unconformably over the Giralia anticline (Hocking et al., 1987). The rigid pre-Upper Carboniferous Gascoyne Platform reacted only marginally to the compressive stresses, which, conversely, greatly affected the more plastic rocks of the younger sequences, producing strike-slip movements and anticlines. It is possible that a minor domal uplift involving the rigid competent sedimentary sequence caused the incompetent sequence to undergo shortening in response to the tectonic stresses. In the rigid body, strains are zero. Such a structural event, with reference to the eastern part of the Exmouth Sub-basin and

the western part of the Merlinleigh Sub-basin, is shown schematically in Figure 24. The strike-slip movements may have been the result of the convergence of the two plastic depositional areas where the northern portion of the Gascoyne Platform narrows (Fig. 21).

Geochemistry

Previous reports dealing with the source potential of the Merlinleigh Sub-basin were constrained by the limited amount of available data, most of which are restricted to the western margin of the basin. Consequently, the conclusions reached by the various authors are highly subjective and varied. There is no doubt that more basic information is required in order to provide a reasonable evaluation.

It is firmly established that hydrocarbons are still being generated within the Merlinleigh Sub-basin (Fugro Douglas Geochemistry Pty Ltd, 1991) or are re-migrating from existing accumulations. Gas shows have been encountered by Kennedy Range 1 at the top of the locally tight Moogooloo Sandstone, where the well probably penetrated a fault. Percival and Cooney (1985) stated that the Callytharra Formation, Cordalia Sandstone, and Byro Group have source-rock potential. Dolan and Associates (1991), among others, reviewed the available information and attempted an evaluation of the source-rock potential of the onshore Carnarvon Basin. Although both the
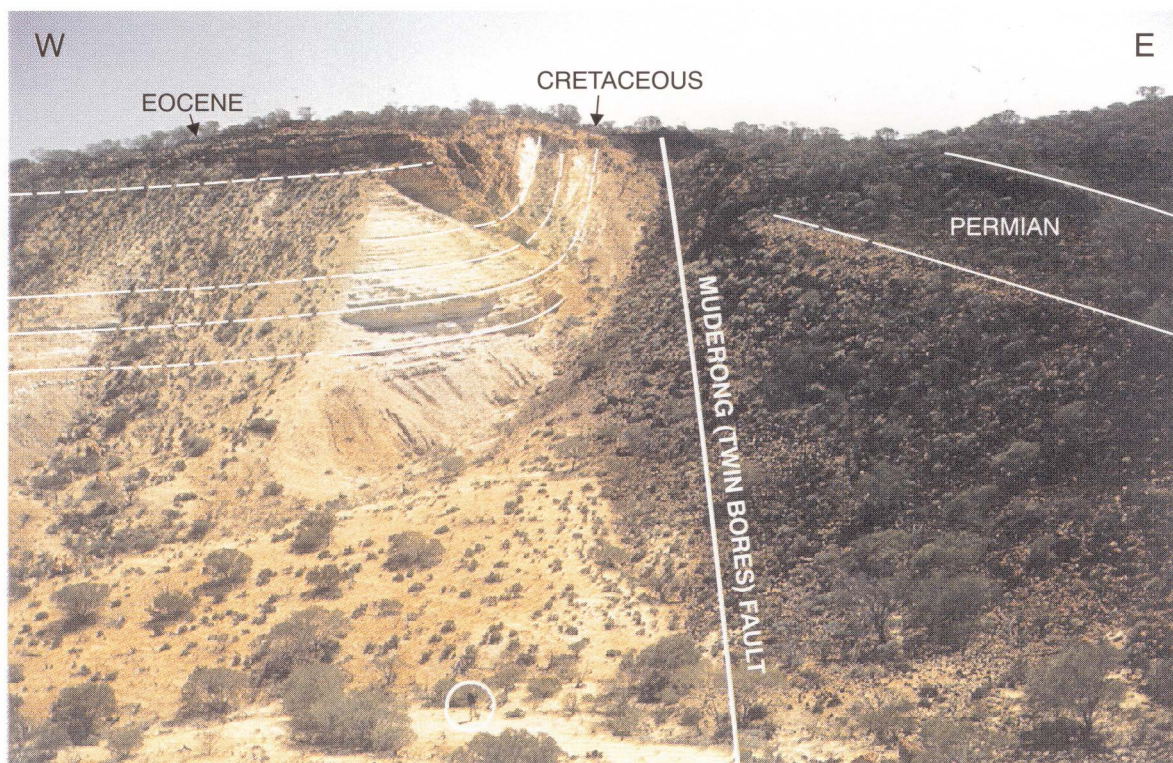
Figure 22. Detail of the Muderong (Twin Bores) Fault, Kennedy Fault System, Merlinleigh Sub-basin: person circled for scale. The substantial drag against the fault plane suggests a major tectonic movement. View north with the Birdrong Sandstone, Windalia Radiolarite, and Muderong Shale on the left, against the Kennedy Group on the right (Photograph by A. J. Mory)

Figure 23. Anticlines and synclines along the western flank of the Kennedy Range, near Tucker Box Spring, Merlinleigh Sub-basin (Photograph by A. J. Mory)

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Figure 24. Shortening of superficial layers on the flanks of a basement arch. Schematically, the incompetent sedimentary rocks represent the Exmouth Sub-basin to the west and the Merlinleigh Sub-basin to the east. The competent rocks represent the Gascoyne Platform
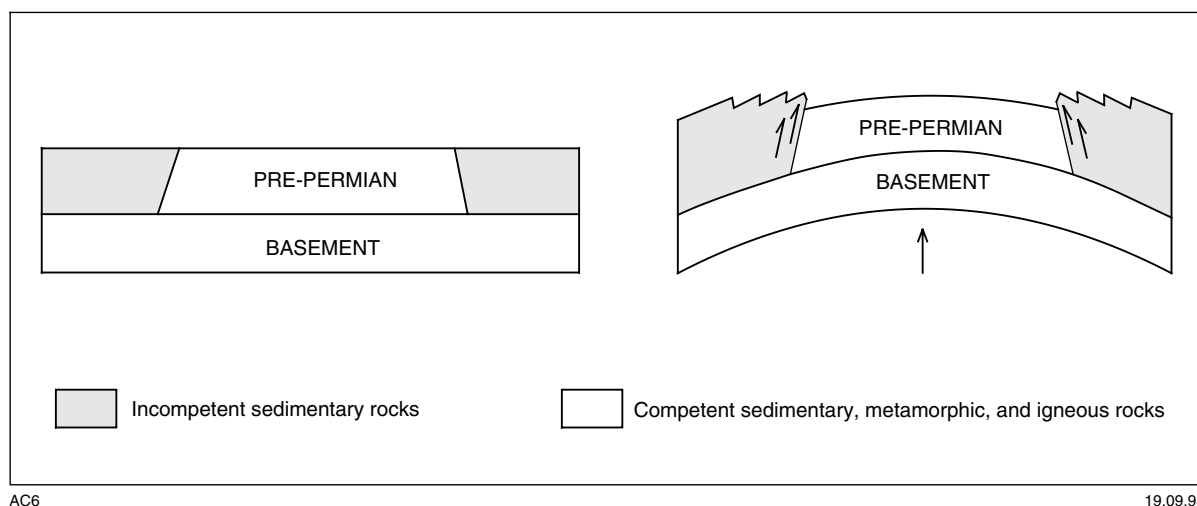
Nannyarra Sandstone and Gneudna Formation may have some source potential, Dolan and Associates (1991) concluded that the Devonian sequence remains an 'enigma'. It is worth noting, however, that in Quobba 1 several samples across the more shale-prone lower part of the Gneudna Formation sequence (Fig. 6) indicated a TOC in excess of 0.5%, with the best yield-potential reaching 3.62 mg/g, whereas screening analyses failed to reveal any source rocks across the upper carbonate interval (Blake et al., 1984). Percival and Cooney (1985) stated that no significant source rocks were found in the mostly carbonate Gneudna Formation penetrated by Quail 1. A sample of oil from the Pendock 1 Gneudna Formation carbonate sequence indicates a probable clastic source rock (Mitchell, 1992). These occurrences suggest that the Gneudna Formation source potential depends on the presence of terrigenous material, with a high content of organic matter. The deposition of terrigenous material is in turn related not only to the basinal position of the sedimentary rocks, but also to the local presence of palaeo-lows.

Within the Permian interval, Dolan and Associates (1991) acknowledged the presence of significant source rocks, both gas (organic material type II) and gas and oil (organic material type III) prone. The Permian is rated the most important of the potential source horizons in the Palaeozoic. More specifically, the source-rock potential of the Wooramel Group is rated good, at least for gas. Dolan and Associates (1991) were less optimistic about the source potential of the Callytharra Formation than Percival and Cooney (1985), and did not consider it to be a potential source rock. They also questioned the source potential of the Byro Group. On the other hand, the oil shows analysed in the Southern Carnarvon Basin are all considered to be indicative of a Palaeozoic source.

In the context of the GSWA Petroleum Initiatives program, geochemical analyses have been carried out on cores from several shallow holes that were drilled for mineral exploration (Fig. 8). The most informative results have been obtained from the Uranerz CDH-8 hole drilled for uranium in 1973 some 17.5 km east-southeast of Moogooree Homestead, and BHP Wandagee 1, which was drilled in 1975, 40 m west of Quail 1, for coal exploration.

Two isolated samples of the Devonian Gneudna Formation from CDH-8 gave TOC and pyrolysis (Rock-Eval) data that suggest the formation has good source potential for gas and oil generation (Fig. 25). It is worth noting that in a world-wide context, the Middle–Late Devonian sequence contains significant source rocks.

The Rock-Eval pyrolysis data from BHP Wandagee 1 (Fig. 26) support the conclusion that the Permian Wooramel Group contains good source rocks in the northern part of the Merlinleigh Sub-basin. The organic richness is very good and the hydrocarbon-generating potential is fair to good (Fig. 27). Kerogen typing based on the Rock-Eval data (Fig. 28), pyrolysis – gas chromatogram (Fig. 29), and pyrolysis – gas-chromatographic kerogen typing (Fig. 30) indicate the presence of kerogen type III, with potential to generate predominantly gas with some oil. These geochemical analyses are part of a study in progress by A. Ghori of the GSWA.

Conversely, in Kennedy Range 1 and Gascoyne 1 the source-rock potential of the Wooramel Group is rated low. This may be related to the depositional environment of the lithostratigraphic unit, as described by Hocking et al. (1987). The dominant palaeocurrent directions indicate that at the time of deposition of the Wooramel Group, the palaeoslope was to the northwest. Depositional conditions were terrestrial to shallow marine with water depth increasing towards the northwest and progressively coarser grained, higher energy deposits accumulating towards the southeast. Percival and Cooney (1985) commented, however, that some hydrocarbon-generation potential may be offered, at least locally, by the Jimba Jimba Calcarenite Member.

In assessing the present source-rock potential, the maturity of the relevant formation must be taken into consideration. The maturity is a function of the temperature reached, which, in turn, depends on the heat flow in the region. The depth of burial remains the overwhelming factor. As discussed in the section dealing with the development of the basin, it is considered that a rifting episode took place during the Late Carboniferous along the western margin of the Merlinleigh Sub-basin. Overmaturity of the Devonian sedimentary rocks in Quail 1 (Percival and Cooney, 1985) can, therefore, be related to this rifting, which was conducive to high heat flow. As Quail 1 was drilled along the western margin of the Permian basin, and very close to the rift, it would be incorrect to extrapolate the Quail 1 maturity data over the entire Permian basin. The reported temperature gradients in the Merlinleigh Sub-basin of 35 to 40°C per kilometre (Moors, 1980) are estimated to be valid only along the western belt, close to the rift. The high geothermal gradients in this case are clearly related to this rifting.

Kimberlite pipes related to the Merlinleigh Sub-Basin western-margin fault zone may also have had some impact. Such a conclusion is supported by work carried out by Nicoll and Gorter (1995), who determined a Conodont Alteration Index (CAI) of 1 from conodont fauna of the Devonian Gneudna Formation type section, and other outcrops, along the less tectonized eastern margin of the Merlinleigh Sub-basin. A CAI of 1 corresponds to a vitrinite reflectance (R_o) value of less than 0.8. Furthermore, a maximum temperature (T max) of 429–430ºC has been derived for the Devonian Gneudna Formation in the Uranerz CDH-8 well, suggesting marginally mature source rocks. Also, the Devonian section penetrated by WAPET Wandagee 1 has not been subject to a very high temperature, because the phosphatic microfossils indicate a CAI of approximately 2 (Nicoll and Gorter, 1995), which corresponds to R_o values ranging from 0.85 to 1.30.

The Permian Wooramel Group section is in the early mature zone of the oil window in Burna 1 (Percival and
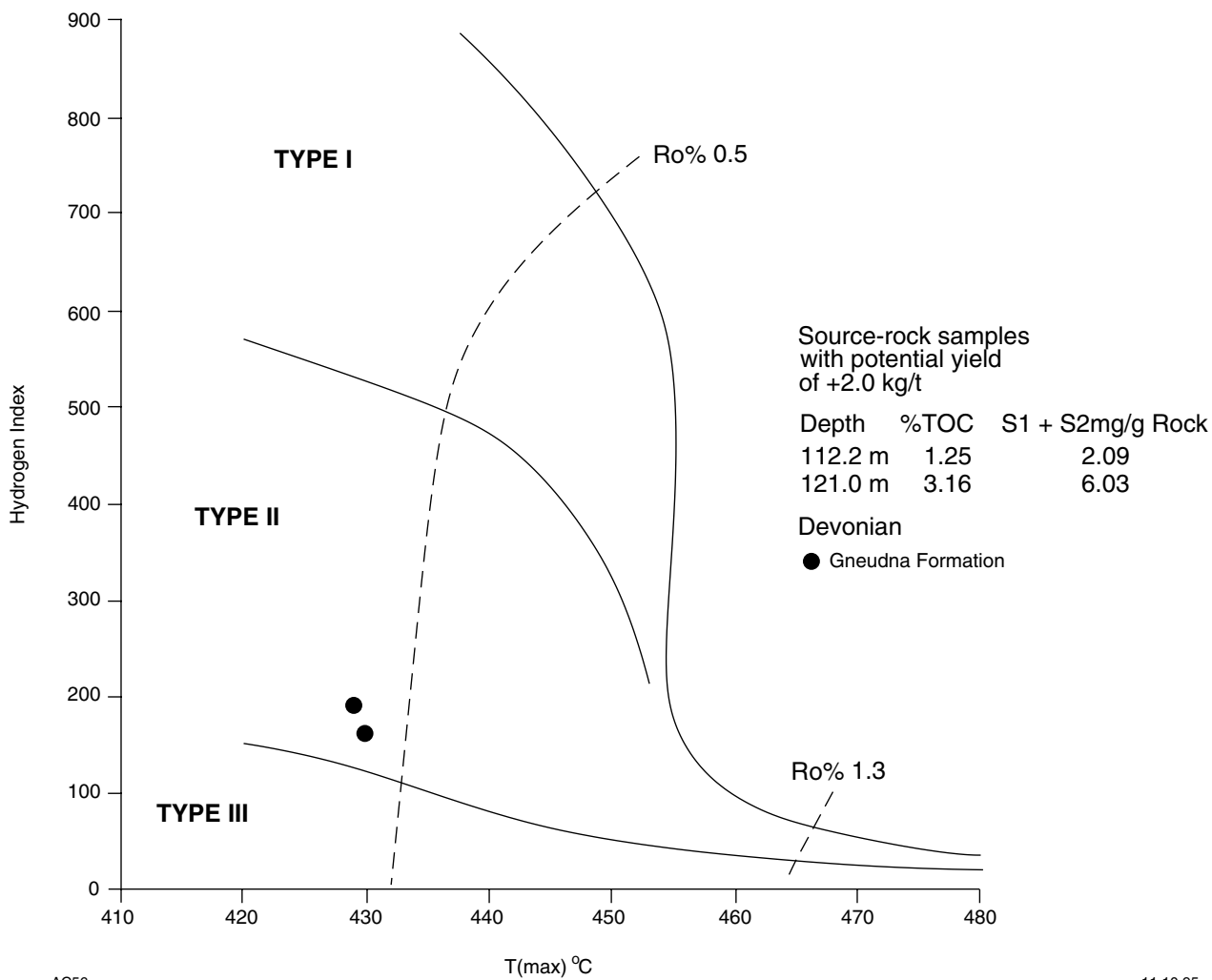

Figure 25. Source-rock potential and kerogen type of the Devonian Gneudna Formation sampled in the Uranerz mineral exploration hole CDH-8
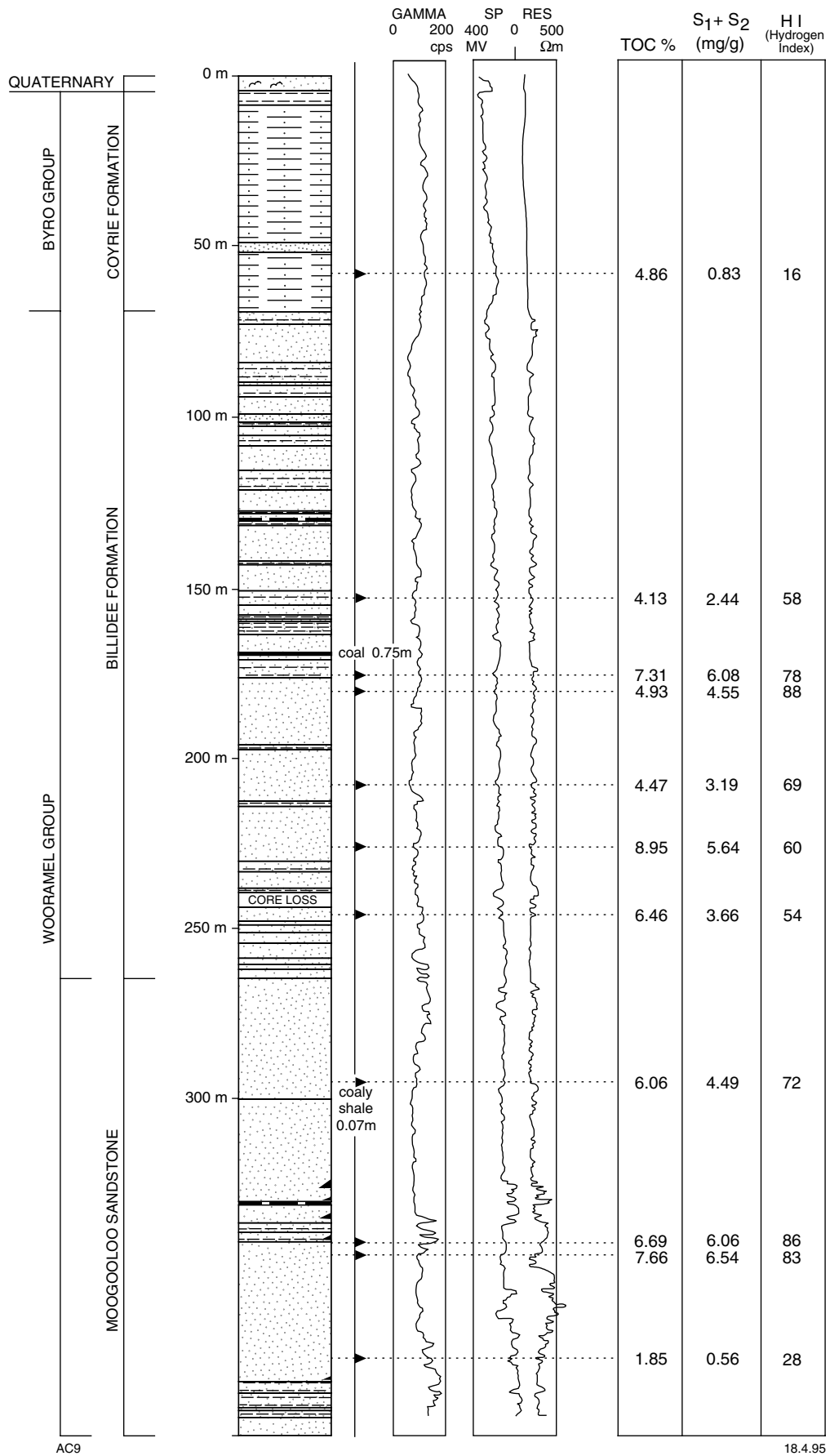
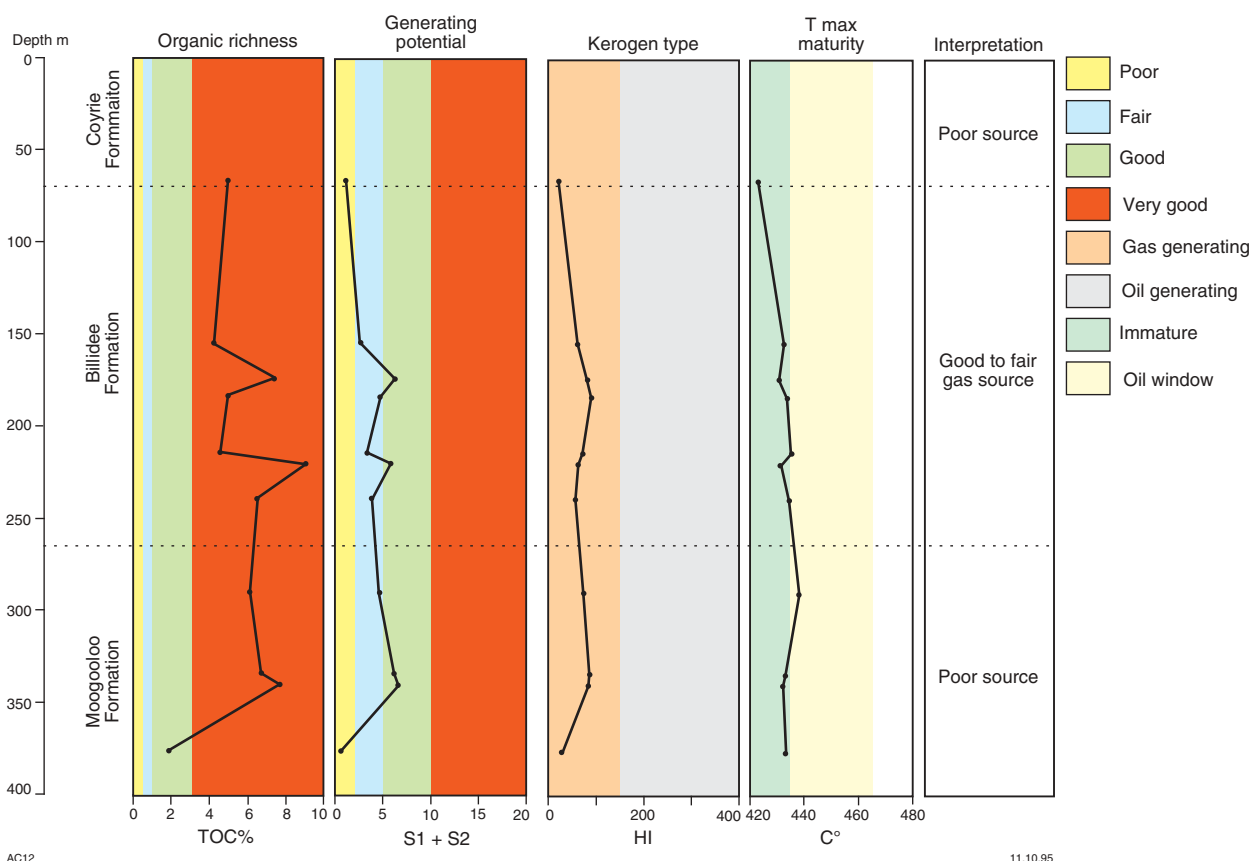**Figure 26. BHP Wandagee 1 well log**

Figure 27. Source-rock potential of the Permian Wooramel Group section from cores in BHP Wandagee 1. GSWA Geotech data, 1994

Cooney, 1985), and appears similar in Gascoyne 1 (GSWA study), or is still immature, as shown in BHP Wandagee 1 (Fig. 27). In Kennedy Range 1 the section below 1600 metres, which includes the Wooramel Group source rocks, appears to be overmature for oil generation as indicated by a sharp increase in palaeotemperature. More data are required to exhaustively evaluate the entire sub-basin. It is conceivable that across the basin the Wooramel Group is mainly within the oil window.

Deposition in the basin virtually ceased in the Late Permian, and the thickness of the overlying Cretaceous sedimentary rocks is very limited, indicating that the level of maturity for hydrocarbon generation within the Merlinleigh Sub-basin was reached at the end of the Permian or soon after. This does not preclude generation of hydrocarbons after the oil window was reached, nor the possibility of re-migration. The increase in heat flow during Miocene tectonism should also have generated additional amounts of hydrocarbons.

Reservoirs

Within the northern part of the Merlinleigh Sub-basin, the three more interesting stratigraphic objectives offering potentially attractive reservoirs are the Devonian Nannyarra and Munabia Sandstones (Lavering, 1982) and the Early Permian Moogooloo Sandstone. Within the southern part of the Merlinleigh Sub-basin and within the Byro Sub-basin only the Moogooloo Sandstone appears to be a possible objective. Also, pre-Devonian objectives may occur in the northwestern segment of the basin, but their evaluation is beyond the scope of this Report. The reservoir potential of the sandy intervals within the Byro Group is rated poor, with the exception of the Nalbia Sandstone, which is commonly at very shallow depth.

Warris (1994) reported that the shallow-marine Nannyarra Sandstone in Wandagee 1 has log-derived porosities in the range of 15–20%, and other wells that penetrated the unit within the onshore Carnarvon Basin encountered sandstones with comparable petrophysical characteristics. However, the outcrops on the eastern margin of the Merlinleigh Sub-basin have a lower potential for hydrocarbons because of the presence of an argillaceous matrix in the reservoir sandstone. Furthermore, in the east, hydrocarbons in the Nannyarra Sandstone could only have migrated from the overlying sedimentary rocks because the Nannyarra Sandstone was deposited on basement rocks.

The mature fluvial Munabia Sandstone and the sandstones of the laterally equivalent Willaraddie Formation overlie potential source rocks and therefore occupy a good stratigraphic position for hydrocarbon entrapment. No specific petrographic study has been carried out on the unit to date. The main weakness of these

Devonian objectives is the source potential of the sequence, which has to be confirmed.

The fluviatile Moogooloo Sandstone has good reservoir qualities where penetrated at shallow depth. Percival and Cooney (1985) report log porosities up to 23%. Good permeabilities also occur locally (Warris, 1994). At greater depths, the porosity deteriorates and the permeability may become too low to be of interest. However, Kennedy Range 1 is the only well that penetrated this formation at great depth, and it may not be a valid test of the reservoir potential of the Moogooloo Sandstone because of the high geothermal gradient encountered in the western belt where the well was drilled. As discussed previously, it is inappropriate to assume that the belt is indicative of the characteristics of the entire basin. A detrimental factor to also consider is that, in places, the Moogooloo Sandstone appears to be more silty. However, the importance of the unit as a potential reservoir cannot be overestimated because the unit is represented by massive, clean quartz sandstone, up to 176 m thick.

Seals

The Nannyarra Sandstone may be adequately sealed by the overlying marine shales of the Gneudna Formation. The seal for the Munabia Sandstone and the Willaraddie Formation is unfortunately more problematic because the overlying Moogooree Limestone may not provide an effective seal.

The Moogooloo Sandstone grades upwards to the siltstones and sandstones of the Billidee Formation, which cannot be relied upon as an effective seal and may actually comprise additional potential reservoirs. An effective seal can, however, be provided by the basal unit of the Byro Group, namely the Coyrie Formation.

Whereas over large parts of the Merlinleigh Sub-basin the Byro Group can offer effective cover, the outcrops of the Byro Sub-basin seem to deny this possibility. The Kennedy Group is not represented — perhaps it was never deposited there — and the Byro sedimentary rocks are restricted to scattered outcrops. The attractive tracts of the
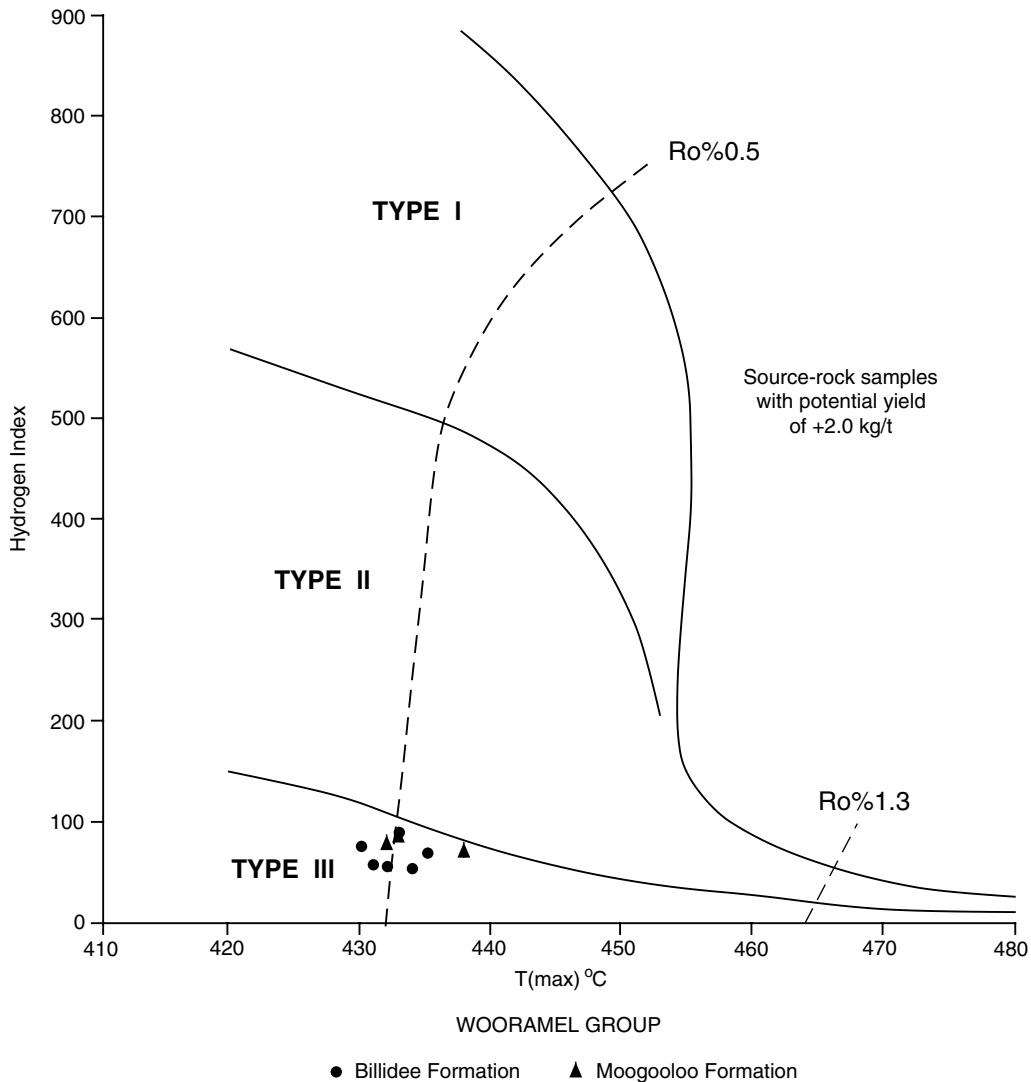

Figure 28. BHP Wandagee 1: Kerogen type

sub-basin for hydrocarbon potential may occur to the south, west of the Darling Fault (Fig. 4), where the Permian is concealed. Both the gravity and magnetic images (Figs 3 and 4) suggest a southwards thickening of the basin. This is consistent with the depth to basement map (Megallaa, 1980), which indicates a thickness of approximately 3000 metres in the depositional centre of the area. This thickening would suggest that younger rocks are present above the Wooramel Group. Alternatively, the Lyons Group may be substantially thicker or older sedimentary rocks are included in the gross thickness. The monotonous sandstone–siltstone sequence of the Badgeradda Group cannot be considered responsible for the estimated thickness because it is more than 10 000 ft (3050 m) thick on its own (Perry and Dickins, 1960). Information from boreholes may be critical in order to resolve the ambiguity.

The Nalbia Sandstone of the Byro Group is unlikely to be sealed effectively.

Traps

The structural setting and the development of the sub-basin indicate that within the Merlinleigh Sub-basin there are two possible effective trap types: tensional fault traps of Late Permian age, and compressional anticlines of Miocene age.

The Late Permian fault traps formed sufficiently early to contain the maximum amount of hydrocarbons generated within the basin because source-rock maturity may have been reached at the end of the Permian or soon after. An effective fault seal represents the critical weakness of this type of trap.

Conversely, the younger, more attractive folded traps of Miocene age may be fed from either post-peak generation or generation resulting from the heat flow related to Miocene tectonism. Secondary migration is also a distinct possibility. The soil-sample survey (Fugro Douglas Geochemistry Pty Ltd, 1991) supports the presence of at least one of these conditions.

Although the surface anticlines appear to be small, Figure 18 demonstrates that subsurface anticlinal traps of Miocene age may cover more than 50 km^2 of aerial closure. The approximate size can be estimated by considering that the Miocene feature is northerly trending and the seismic section across it is orthogonal to the structure.

Hydrocarbon potential

In summary, the most attractive plays in the Merlinleigh Sub-basin are as follows:

Devonian: Sandstones of the Nannyarra Sandstone covered and sourced by the Gneudna shale.
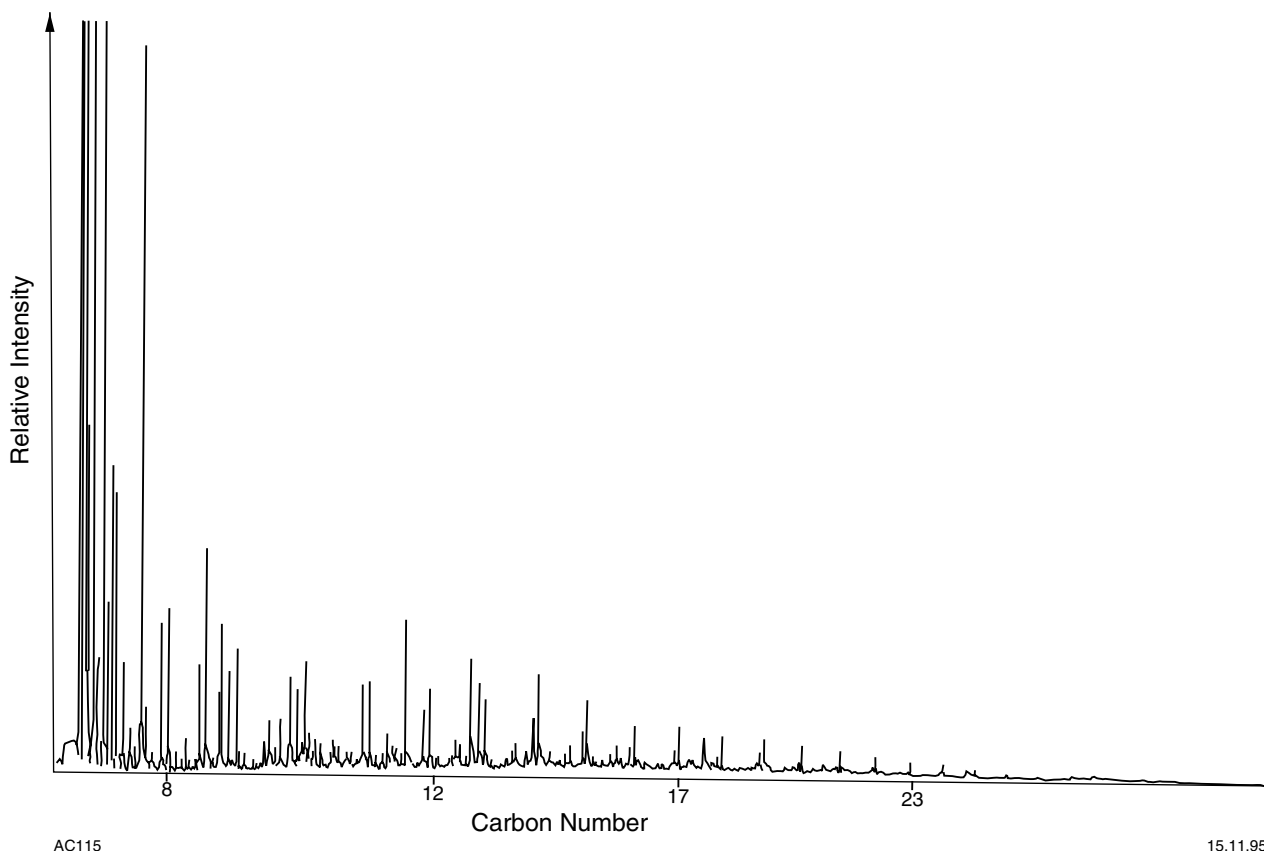

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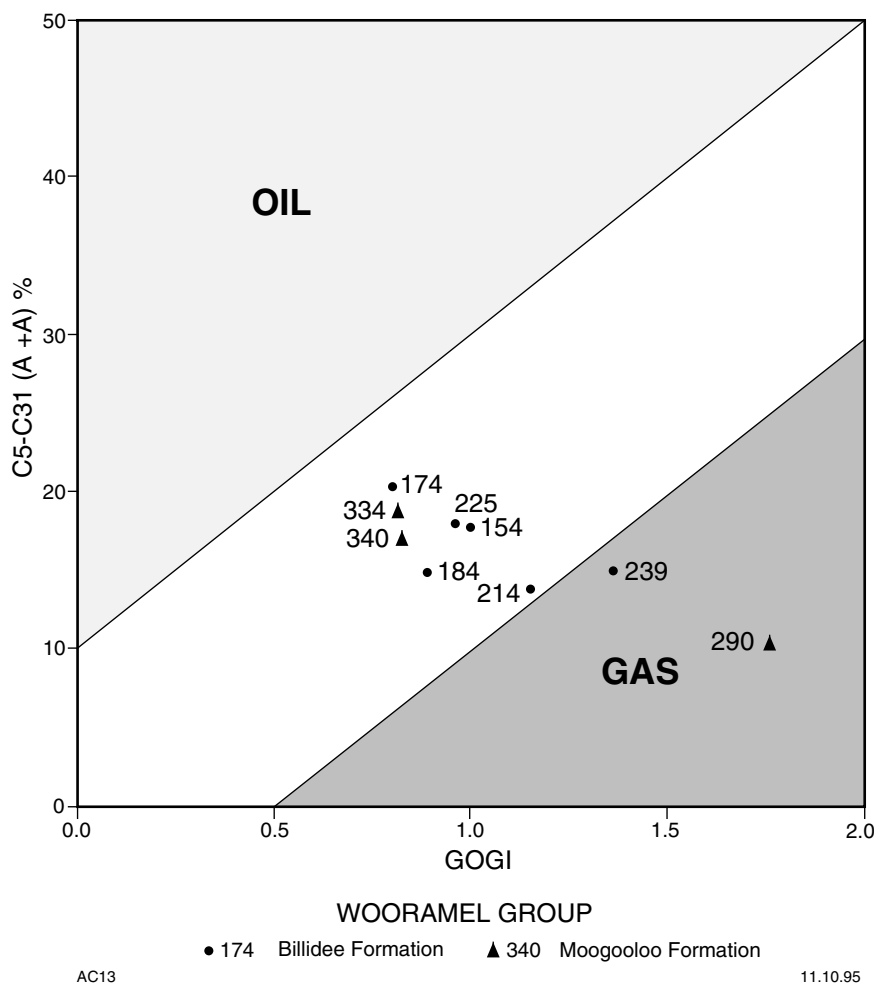Figure 29. BHP Wandagee 1: Pyrolysis – gas chromatogram (core 174 m)

Figure 30. BHP Wandagee 1: Pyrolysis – gas-chromatogram kerogen typing

Permian: Sandstones of the Moogooloo Sandstone, and possibly the Billidee Formation, sealed by the Coyrie Formation and sourced by the entire Wooramel Group.

The Devonian play is not yet mature. The structural relationships between the Devonian to Early Carboniferous sedimentary rocks and those of Late Carboniferous to Early Permian age are not entirely clear. Hocking et al. (1987) states that these two cycles are unconformable, but no clear angular unconformity has been recognized in the seismic sections. Furthermore, the source-rock potential of the Gneudna Formation needs to be confirmed.

The Permian play is mature. Well-defined structural leads are identified (Figs 18 and 19) and others are likely to be present. Good source-rock potential is documented: both the richness and thickness of the Wooramel Group are comparable with that of the Irwin River Coal Measures, which are critical to gas production in the Perth Basin. Further seismic control is required in order to upgrade a prospect to the drilling stage.

Conclusions

Oil exploration in the Merlinleigh and Byro Sub-basins commenced in the 1930s and was resumed in earnest in the 1950s. Two main phases of petroleum exploration have been carried out, by WAPET in the 1960s and by ESSO in the 1980s. Each company drilled two exploration wells. The oil wells failed to encounter hydrocarbons, but the ineffective trapping mechanism makes the tests not definitive.

Following the two unsuccessful drilling campaigns, oil companies have displayed only limited interest in the area, although effective source rocks, reservoirs, seals, and traps are present. Concern about deterioration of reservoir potential at fairly shallow depths is considered to be justified only along the heavily faulted western margin of the sub-basins. Anticlinal traps do not rely on fault seals. Several untested structural traps occur in the region.

It is concluded that the hydrocarbon potential of the two sub-basins is still to be evaluated. New investments may handsomely reward the explorationist willing to undertake further exploration activities in the area.

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Appendix

GSWA Petroleum Initiatives projects

The following projects have been carried out or are planned by the GSWA on the onshore Carnarvon Basin within the context of the current Petroleum Initiatives Program. This program was proposed in order to provide the oil industry with further information on less-explored areas and to focus future exploration activities towards the best targets.

- A geochemical review of the Merlinleigh Sub-basin, incorporating tabulation of existing and newly acquired analytical data.

- A gravity and aeromagnetic survey of the Merlinleigh Sub-basin, in order to provide additional structural information to complement the existing seismic data.

- The drilling of Gneudna 1 corehole to evaluate the hydrocarbon source-rock potential of the Devonian Gneudna Formation. Devonian rocks are highly productive world-wide, as is the case in Canada and Russia.

- The drilling of Ballythanna 1 corehole to evaluate the hydrocarbon source-rock potential of the Permian Callytharra and Carrandibby Formations in both the Merlinleigh and Byro Sub-basins. This potential is rated variably by the industry.

- Geochemical analyses of the two planned coreholes (Gneudna 1 and Ballythanna 1).

- A comprehensive review of the exploration geology, geophysics, and geochemistry of the Merlinleigh Sub-basin.

- An analysis of the results of the petroleum exploration activities in the North West Cape.

- An evaluation of the hydrocarbon potential of the North West Cape area.

- An evaluation of the Giralia area, Carnarvon Basin.