Department of
Industry and Resources

REPORT
86

A SUMMARY OF THE GEOLOGICAL EVOLUTION AND PETROLEUM POTENTIAL OF THE SOUTHERN CARNARVON BASIN WESTERN AUSTRALIA

by A. J. Mory, R. P. Iasky, and K. A. R. Ghori

Geological Survey of Western Australia

GEOLOGICAL SURVEY OF WESTERN AUSTRALIA

REPORT 86

A SUMMARY OF THE GEOLOGICAL EVOLUTION AND PETROLEUM POTENTIAL OF THE SOUTHERN CARNARVON BASIN, WESTERN AUSTRALIA

by
A. J. Mory, R. P. Iasky, and K. A. R. Ghori

Perth 2003

REFERENCE
The recommended reference for this publication is:
MORY, A. J., IASKY, R. P., and GHORI, K. A. R., 2003, A summary of the geological evolution and petroleum potential of the Southern Carnarvon Basin, Western Australia: Western Australia Geological Survey, Report 86, 26p.

National Library of Australia
Cataloguing-in-publication entry

Mory, A. J. (Arthur John), 1953–
A summary of the geological evolution and petroleum potential of the Southern Carnarvon Basin, Western Australia.

Bibliography.
ISBN 0 7307 8927 6

1. Petroleum — Geology — Western Australia — Carnarvon Basin.
2. Geolog — Western Australia — Carnarvon Basin.
I. Iasky, R. P. (Robert Paul), 1956– .
II. Ghori, K. A. R.
III. Geological Survey of Western Australia.
IV. Title. (Series: Report (Geological Survey of Western Australia); 86).

553.28099413

ISSN 0508–4741

Grid references in this publication refer to the Geocentric Datum of Australia 1994 (GDA94). Locations mentioned in the text are referenced using Map Grid Australia (MGA) coordinates, Zone 50. All locations are quoted to at least the nearest 100 m.

Copy editor: K. A. Blundell
Cartography: T. Pizzi
Desktop Publishing: K. S. Noonan and K. A. Blundell

Published 2003 by Geological Survey of Western Australia

Copies available from:
Information Centre
Department of Industry and Resources
100 Plain Street
EAST PERTH, WESTERN AUSTRALIA 6004
Telephone: (08) 9222 3459 Facsimile: (08) 9222 3444
This and other publications of the Geological Survey of Western Australia are available online through the Department's bookshop at www.doir.wa.gov.au

Cover photograph:
Limestone karst towers (7–8 m high) in the Lower Permian Callytharra Formation, near Coronation Bore on Bidgemia Station, Southern Carnarvon Basin

Contents

Appendix

Figures

Table

A summary of the geological evolution and petroleum potential of the Southern Carnarvon Basin, Western Australia

by
A. J. Mory, R. P. Iasky, and K. A. R. Ghori

Abstract

The Southern Carnarvon Basin consists of two main regions: a western platform (Gascoyne Platform) with a ?Cambrian to Lower Carboniferous succession that has mostly flat-lying Cretaceous–Cainozoic cover; and an eastern set of half-grabens (Merlinleigh and Byro Sub-basins) forming a single mid-Carboniferous – Permian depocentre, now separated by gneissic basement of the Carrandibby Inlier. The Merlinleigh Sub-basin shares a Devonian to Lower Carboniferous succession with the Gascoyne Platform, but the two regions otherwise have little in common. The low thermal maturity of the Silurian section implies little, if any, mid-Carboniferous – Permian deposition across the Gascoyne Platform, whereas up to 5000 m of strata of that age were deposited in the Merlinleigh and Byro Sub-basins. The major tectonic events in the basin, evident from seismic and outcrop data, were in the mid-Carboniferous – Early Permian, mid- to Late Permian, Early Cretaceous, and early Neogene. These periods of faulting and folding are consistent with AFTA and vitrinite reflectance data from the Gascoyne Platform, which indicate palaeothermal-cooling episodes during the Permian, Late Jurassic, and early Neogene. No regional deformation is apparent prior to the mid-Carboniferous.

Geochemical analyses indicate that the best petroleum source beds are within the Silurian Coburn Formation, Devonian Gneudna Formation, and Lower Permian Wooramel and Byro Groups. Silurian source beds have organic richness of over 7% TOC, potential yield ($S_1 + S_2$) of up to 38 mg/g, and hydrogen index of up to 505, whereas Devonian source beds have organic richness of up to 13.5% TOC, potential yield of up to 40 mg/g, and hydrogen index of up to 267. However, all of these beds are thin and probably of limited extent. By comparison, Permian source beds within the Merlinleigh and Byro Sub-basins appear to be thick and widespread. The organic richness of these beds is up to 16% TOC with an average of 7%, and potential yield of up to 12 mg/g with an average of 6 mg/g, and are predominantly gas generating. Geohistory modelling indicates that petroleum generation (and consequently migration) from Silurian and Devonian source beds peaked during the Permian, whereas generation from Permian source beds peaked during the Triassic. Therefore, on the Gascoyne Platform, mid-Carboniferous – Early Permian structures are the most prospective, even though they may have been breached by the later tectonic events, whereas hydrocarbon accumulations within the Merlinleigh and Byro Sub-basins are likely only in younger structures of Early Cretaceous or Miocene age.

KEYWORDS: stratigraphy, structure, petroleum potential, Southern Carnarvon Basin, Gascoyne Platform, Merlinleigh Sub-basin, Byro Sub-basin.

Introduction

The Southern Carnarvon Basin covers most of the onshore part of the greater Carnarvon Basin, and includes an offshore portion that extends south of the Rough Range Fault system and north of the Abrolhos Sub-basin (Fig. 1). The basin has largely Palaeozoic fill, and was formally distinguished from the northern, mostly Mesozoic, offshore part of the basin by Hocking et al. (1994) and Hocking (1994), although the distinction had been made previously on an informal basis. A Palaeozoic succession is probably widespread throughout the Northern Carnarvon Basin, but is at a considerable depth in most of the basin, except in marginal areas such as the Peedamullah Shelf and Onslow Terrace (Fig. 1). The similarity of the Palaeozoic section in those sub-basins to that in the Southern Carnarvon Basin indicates that they were once part of the same depositional province, at least till the end of the Permian. Unlike older rocks, the Carboniferous–Permian succession extends well into the Perth Basin, indicating that deposits of this age formed as part of a much larger province.

The Southern Carnarvon Basin comprises three Palaeozoic sub-basins: the Gascoyne Platform to the west, and the Merlinleigh and Byro Sub-basins to the east (Fig. 1). The Bidgemia Sub-basin, east of the Weedarra Inlier (Condon, 1954), is now included within the Merlinleigh Sub-basin. All sub-basins have predominantly

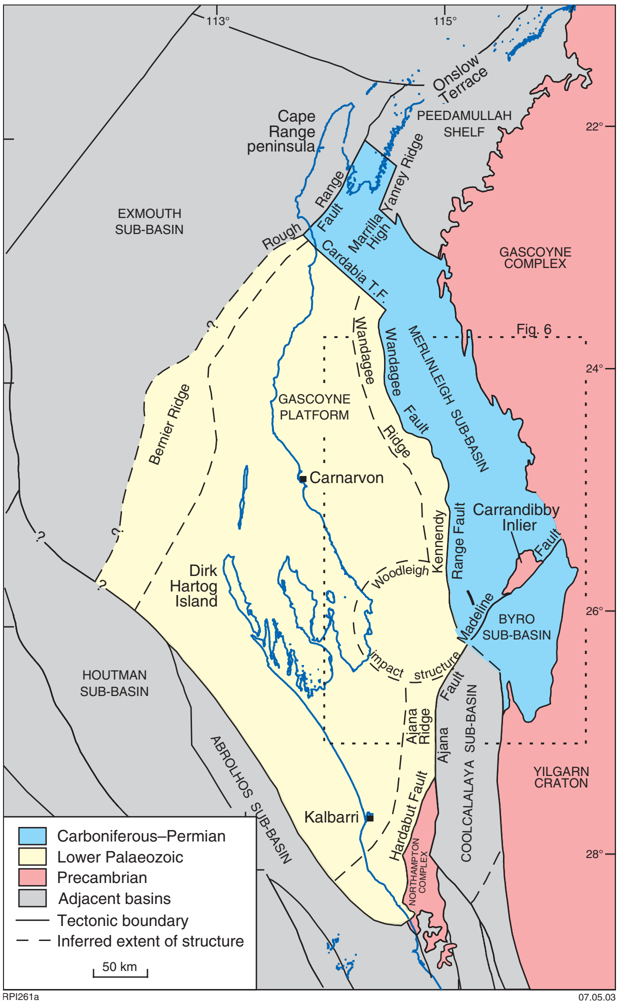

Figure 1. Tectonic elements of the Southern Carnarvon Basin and adjoining basins

Palaeozoic fill. A thin cover of Mesozoic (mostly Cretaceous) and Cainozoic strata extends across the Gascoyne Platform and just into the Merlinleigh Sub-basin. The Gascoyne Platform extends offshore and contains a ?Cambrian to Carboniferous sedimentary succession; from the mid-Carboniferous to the Early Cretaceous it was a relative structural high. Basement ages in the Woodleigh impact structure imply that the Neoproterozoic Pinjarra Orogen underlies at least part of the Gascoyne Platform. To the east, Palaeoproterozoic gneissic basement of the Carrandibby Inlier separates the Merlinleigh and Byro Sub-basins, which may have been a single depocentre extending south into the Coolcalalaya Sub-basin, and farther south into the main part of the Perth Basin. Along the eastern margin of the Merlinleigh and Byro Sub-basins, the mid-Carboniferous to Permian succession onlaps the Archaean Yilgarn Craton and Palaeoproterozoic Gascoyne Complex. To the northwest this succession extends along the northern end of the Gascoyne Platform to the Rough Range Fault (Giralia area; Crostella and Iasky, 1997), which marks the northwestern boundary with the Mesozoic depocentre of the Exmouth Sub-basin in the Northern Carnarvon Basin.

Along the Cape Range peninsula, which is part of the Exmouth Sub-basin, a thick Mesozoic section overlies a Palaeozoic section that is inferred, from gravity data, to be much thinner than in the Southern Carnarvon Basin (Iasky et al., 2003). To the south the Gascoyne Platform overlies shallow basement, presumably the upper Mesoproterozoic to lower Neoproterozoic Northampton Complex, although in outcrop the contact is faulted.

The Bernier Ridge is the northwestern boundary of the platform, although the paucity of data on the ridge makes it difficult to precisely place the boundary. To the southwest the contact with the largely Mesozoic Abrolhos and Houtman Sub-basins is along a major westerly to west-southwesterly dipping fault system (Bradshaw et al., 2003). The narrow Wandagee and Ajana Ridges define the eastern margin of the Gascoyne Platform. To the south of the Gascoyne Platform, these ridges are disrupted by the Woodleigh impact structure (Mory et al., 2000, 2001; Iasky et al., 2001) of Late Devonian age (Uysal et al., 2001, 2002), suggesting that prior to the impact these ridges were a single entity.

Previous investigations

Exploration of the onshore Southern Carnarvon Basin began in 1902 with the drilling of the first artesian bore, Pelican Hill 1 (Maitland, 1909). Early evaluations of the petroleum potential depended largely on surface mapping (Raggatt, 1936) and artesian bores (Clapp, 1926; Condit, 1935; Hobson, 1936), the results of which were summarized by Playford and Chase (1955). Although mineral exploration in the basin began early last century, it was not until the 1970s, when deep drilling and geophysical surveys were carried out, that mineral exploration data became useful in evaluating the petroleum potential of the basin.

The Bureau of Mineral Resources (BMR, now Geoscience Australia) commenced systematic, regional aeromagnetic and radiometric surveys in the basin in the 1950s, followed by outcrop mapping in conjunction with stratigraphic drilling (Condon, 1965, 1967, 1968). West Australian Petroleum Pty Ltd (WAPET) also began onshore exploration of the basin in the 1950s by mapping outcrop and drilling stratigraphic wells on anticlinal features and topographic highs. In 1953 the company made the first oil discovery in Western Australia with its first well on the Rough Range Anticline, Rough Range 1, prompting further exploration of the basin, but without success onshore. Of the 40 follow-up wells drilled in the Cape Range peninsula over the following 40 years, only Roberts Hill 1 and Parrot Hill 1 recovered significant hydrocarbons. Farther south, WAPET drilled shallow stratigraphic tests on anticlinal structures without discovering any hydrocarbons. The most prolific drilling was carried out on Dirk Hartog Island, where the company drilled 16 shallow structure holes to delineate an anticlinal structure before testing it with Dirk Hartog 17B. Other companies contributing to the early phase of petroleum exploration, also without success, include Continental Oil Company (Conoco), Magellan Petroleum Pty Ltd, Oceania, and Marathon.

Exploration in the offshore part of the basin began in the mid- to late 1960s with a regional aeromagnetic survey followed by regional seismic surveys. The first offshore well in the Southern Carnarvon Basin (Pendock 1) was drilled in 1969 by Genoa Oil (Geary, 1970), and was followed by Edel 1 in 1972 by Ocean Ventures. With the exception of Conoco, who retained an interest in the southern offshore Gascoyne Platform, petroleum exploration in the Southern Carnarvon Basin almost ceased by the mid-1970s, mainly because of successes in the Northern Carnarvon Basin, including Barrow Island in 1964, Legendre in 1968, Goodwyn and North Rankin in 1971, and Lambert in 1973. The most notable onshore activity at the end of the 1970s was mapping by the Geological Survey of Western Australia (GSWA), which was synthesized by Hocking et al. (1987).

In the latter half of the 1970s, mineral exploration in the basin commenced in earnest, particularly with drilling for coal and uranium in 1976, and exploration for diamonds on the Wandagee Ridge and base metals in the Permian succession in 1978–79. In 1981, geochemical results from shallow drilling for oil shale by ESSO in the Merlinleigh Sub-basin (Emmett, 1981) prompted the company to explore for petroleum in a more conventional manner. The results after two seismic surveys and two shallow tests (Gascoyne 1 and Burna 1) were disappointing (Percival and Cooney, 1985), although they delineated good source potential in the Permian succession.

In the 1990s relatively little exploration took place onshore. Empire Oil and Gas NL drilled Carlston 1 in 2002 on the basis of seismic data acquired in 1994 near the western margin of the Gascoyne Platform. Shell Australia and Woodside Energy Ltd began exploration across the boundary between the Gascoyne Platform and the southern part of the Exmouth Sub-basin in 2001–02, the early results of which are summarized in Partington et al. (2003).

In late 1993, GSWA commenced a program to re-evaluate the petroleum potential of the Southern Carnarvon Basin, commencing with the Merlinleigh Sub-basin. In the following decade a series of reports were published on individual sub-basins or areas (including some adjacent areas) and on specific topics, such as source rock and reservoir character (Table 1). More-detailed accounts of previous exploration in the region can be

Table 1. Summary of GSWA publications on the Southern Carnarvon Basin and adjacent areas, 1994–2003 (available as PDFs, included on the CD accompanying this Report)

Area or topic	*Short title*	*Reference*
Merlinleigh Sub-basin	Evolution and petroleum potential	Crostella (1995a)
	Giralia area	Crostella and Iasky (1997)
	Permian stratigraphy and palynology	Mory and Backhouse (1997)
	Reservoir character (Moogooloo Sandstone)	Harvord (1998)
	Source rocks	Ghori (1996)
	Structure and petroleum potential	Iasky et al. (1998a)
Gascoyne Platform	Geology and petroleum potential (onshore)	Iasky and Mory (1999)
	Geophysics of the Woodleigh impact structure	Iasky et al. (2001)
	Gneudna Formation	Gorter et al. (1998)
	Silurian–Devonian source-rock and thermal history	Ghori (2002)
	Structure and petroleum prospectivity	Iasky et al. (2003)
Stratigraphic drilling	Ballythanna 1, Byro Sub-basin	Mory (1996b)
	Barrabiddy 1, 1A, Wandagee Ridge	Mory and Yasin (1999)
	Boologooro 1, Gascoyne Platform (basic)	Mory and Dixon (2002b)
	Coburn 1, Gascoyne Platform	Yasin and Mory (1999a)
	Edaggee 1, Gascoyne Platform (basic)	Mory and Dixon (2002c)
	Edaggee 1, Gascoyne Platform (interpretation)	Dixon et al. (2003a)
	Gneudna 1, Merlinleigh Sub-basin	Mory (1996a)
	Mooka 1, Gascoyne Platform	Mory and Yasin (1998)
	Woodleigh 1, 2/2A, Woodleigh impact structure	Mory et al. (2001)
	Yaringa East 1, Gascoyne Platform	Yasin and Mory (1999b)
	Yinni 1, Gascoyne Platform (basic)	Mory and Dixon (2002a)
	Yinni 1, Gascoyne Platform (interpretation)	Dixon et al. (2003b)
Adjacent areas	Abrolhos Sub-basin	Crostella (2001)
	Coolcalalaya Sub-basin, Perth Basin	Mory et al. (1998a)
	Irwin Terrace, Perth Basin	Le Blanc Smith and Mory (1995)
	Northern Perth Basin (hydrocarbon potential)	Crostella (1995b)
	Northern Perth Basin (stratigraphy and structure)	Mory and Iasky (1996)
	North West Cape	Crostella (1996)
	Peedamullah Shelf and Onslow Terrace	Crostella et al. (2000)
Other	Basin subdivisions	Hocking (1994)
	Field guide	Hocking (2000)

found in these reports, in particular Crostella (1996), Iasky et al. (1998a, 2003), Iasky and Mory (1999), and Crostella et al. (2000). Eleven stratigraphic wells were also drilled during this program (Table 1). This Report summarizes and integrates that work and the petroleum potential of the basin.

Stratigraphy

Cambrian–Ordovician

The oldest part of the succession in the Southern Carnarvon Basin is an unnamed unit, below the Tumblagooda Sandstone (Figs 2 and 3), apparent on seismic sections from the offshore southwestern part of the Gascoyne Platform, where it has an estimated thickness of about 2000 m. The unit is unconformable on older units, but it is uncertain if it extends farther north, where seismic data quality is poor, or onshore, where there is little seismic data and the unconformity is difficult to identify. Near Edel 1 the unit displays high-amplitude, continuous, parallel reflectors, indicating consistent bedding (Iasky et al., 2003). An Ordovician or older age is presumed (based on the age of the Tumblagooda Sandstone). Therefore it may be coeval with redbed sandstone and siltstone facies at the base of Wandagee 1 (811–1073 m), or the overlying dolomite and mudstone (399–811 m) from which an apparently in situ earliest Ordovician conodont fauna was extracted (from core 5; 704–708 m; Mory et al., 1998b; Iasky and Mory, 1999).

The Tumblagooda Sandstone (Clarke and Teichert, 1948) is dominated by redbed sandstone facies, with rare siltstone and mudstone, which were deposited in a braided fluvial to coastal setting (Hocking, 1991). Trewin (1993a,b), however, interpreted parts of the succession as an eolian sandsheet. Seismic mapping indicates that the Tumblagooda Sandstone ranges in thickness from about 2000 m near Edel 1 to about 3500 m near the Ajana Ridge (Iasky et al., 2003).

Even though there is no unambiguous internal evidence for its age, the Tumblagooda Sandstone cannot be younger than mid-Llandovery (Early Silurian), since Telychian (upper Llandovery) conodont faunas have been identified in the overlying Ajana Formation (Dirk Hartog Group) in Coburn 1. These faunas were used to imply a Late Ordovician age for the unit (Mory et al., 1998b), but an older age is possible. Although the diverse ichnofauna described by Trewin and McNamara (1995) is not particularly age diagnostic, paddle impressions associated with some arthropod trackways suggest that eurypterids were present, thereby indicating the middle part of the formation can be no older than Arenig (Early–Middle Ordovician; McNamara, K., 2003, written comm.). Seismic data indicate that the Palaeozoic section thins onto the Wandagee Ridge, where Wandagee 1 was drilled, but are of too poor quality to show whether the section below 811 m in Wandagee 1 is part of the Tumblagooda Sandstone or a separate, older unit. An alternative, but less likely, interpretation is that the Tumblagooda Sandstone is Cambrian in age with a break (up to 60 m.y.) between it and the overlying Dirk Hartog Group in the southern part of the platform. Iasky et al. (2003) raised the possibility that the section in Wandagee 1 might correlate with the uppermost part of the Badgeradda Group described by Perry and Dickens (1960), even though the facies are dissimilar.

The oxidized nature of the overlying siltstone (Marron Member in the Ajana Formation, Dirk Hartog Group; Mory et al., 1998b) implies this member is genetically related to the redbed facies below, rather than the overlying shallow-marine carbonate and mud facies. Thus, although minor faults appear to truncate at, or near, the upper contact of the Tumblagooda Sandstone (Iasky et al., 2003, plate 10), any break at this level is likely to be minor, at least in the southern part of the Gascoyne Platform.

Silurian

The Dirk Hartog Group conformably or disconformably overlies the Tumblagooda Sandstone north of Kalbarri 1, but is absent farther south, probably due to late Palaeozoic or Mesozoic erosion. Hocking (1991) raised the possibility that redbed facies east of the Northampton Complex correlate with the Dirk Hartog Group based on the trace fossil assemblage, implying up-palaeoslope lateral facies change in the lower Dirk Hartog Group. The group was deposited in a relatively restricted marine environment, with brief connections to an open-marine environment throughout the Silurian. The group has been dated from low-diversity conodont faunas and divided into the Ajana, Yaringa, and Coburn Formations (Mory et al., 1998b). Dolomitic carbonate in Wandagee 1 (399–811 m), similar to that of the Dirk Hartog Group, yielded an Early Ordovician conodont fauna (Mory et al., 1998b), but from seismic data it is unclear whether this section is continuous with the Dirk Hartog Group, and therefore part of it, or a separate older unit.

The Llandovery Ajana Formation, at the base of the Dirk Hartog Group, contains a basal oxidized siltstone (Marron Member) overlain by shoaling-up cycles (Gorter et al., 1994) of grey sandy mudstone, laminated dolomitic mudstone, and wackestone. It is possible that the formation extends into the Merlinleigh Sub-basin, but it is not present on the eastern margin of that sub-basin due to either non-deposition or mid-Devonian erosion. Alternatively, the ?Cambrian – Lower Ordovician section in Wandagee 1 may be equivalent to the interval below 3206 m in Quail 1, but there is no palaeontological evidence from the latter section to corroborate such a correlation. The Yaringa Formation, of late Llandovery age, overlies the Ajana Formation and consists mainly of dolomite and evaporite (mostly halite), which Mory et al. (1998b) tentatively correlated with a predominantly sandstone interval in Pendock 1 (2192–2286 m). The Coburn Formation, of Wenlock age, is mainly dolomitic carbonate. Because the formation lies disconformably on the Marron Member in the eastern part of the platform (Mory et al., 1998b; Iasky and Mory, 1999), the unit may also be paraconformable on the Yaringa Formation farther west.

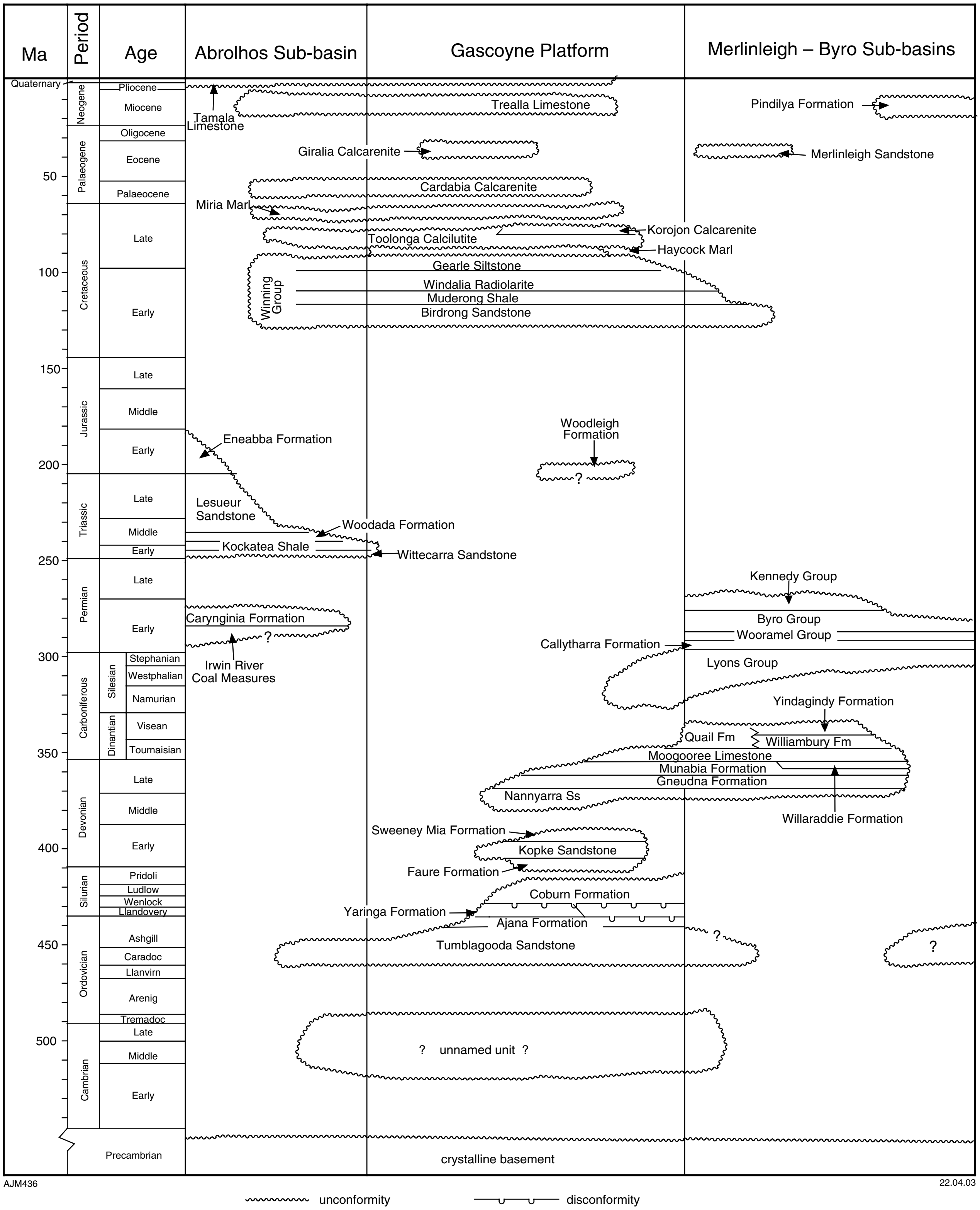

Figure 2. Regional stratigraphy of the Abrolhos Sub-basin, Gascoyne Platform, and Merlinleigh and Byro Sub-basins

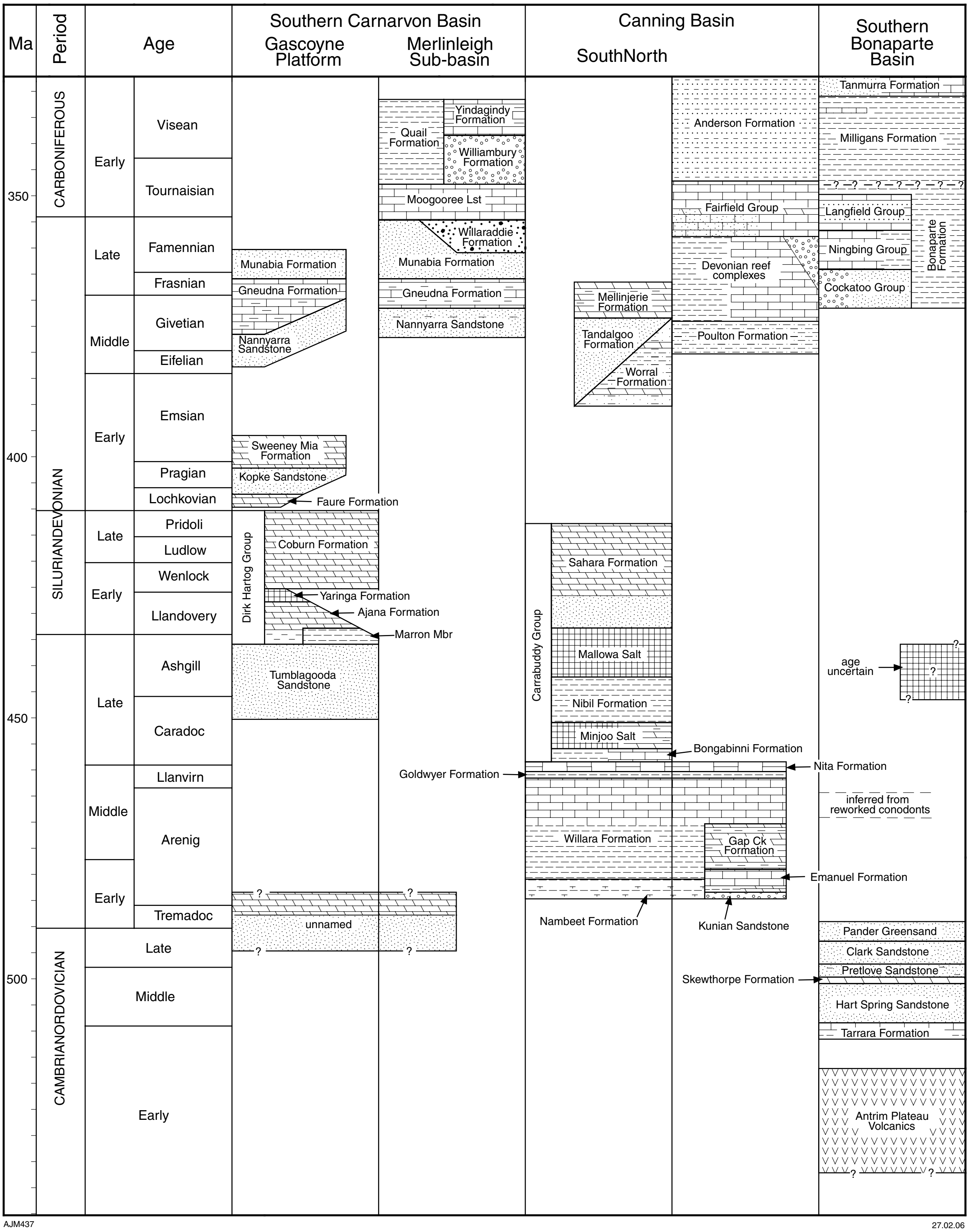

Figure 3. Correlation of the Cambrian – Lower Carboniferous succession in the Southern Carnarvon, Canning, and Southern Bonaparte Basins (after Jones et al., 1997, 1998; Nicoll et al., 1998)

There are insufficient data to estimate the thickness of the Dirk Hartog Group in most of the onshore area. The maximum known thickness of 740 m is in Dirk Hartog 17B. Isopachs based on seismic data show that the group thickens to about 1100 m in the northern part of Shark Bay (Iasky et al., 2003). The group thins to the east and south, and is absent below the Lower Triassic in Edel 1 and Livet 1, presumably due to late Palaeozoic erosion. The hiatus between the Dirk Hartog Group and overlying Lower–Upper Devonian units (Fig. 3) identified by Gorter et al. (1994) is not apparent on seismic data (Iasky et al., 2003).

Lower Devonian

The Lower Devonian succession is made up of the Faure Formation (base), Kopke Sandstone, and Sweeney Mia Formation (top) and is known only from the Gascoyne Platform (Fig. 2; Iasky and Mory, 1999).

The Lower Devonian Faure Formation consists of mudstone, dolomite, and gypsum deposited in a low-energy, saline to hypersaline, shallow-water environment under arid conditions (Yasin and Mory, 1999a). The formation has been intersected in five wells in the southern Gascoyne Platform (Coburn 1, Hamelin Pool 1 and 2, Tamala 1, and Yaringa 1), where it ranges in thickness from 72 to 149 m. The Kopke Sandstone conformably overlies the Faure Formation, and is an upward-coarsening redbed unit with minor dolomite and siltstone beds near the base, and was deposited in deltaic to fluvial environments (Yasin and Mory, 1999a). The unit has been identified in the central and southern part of the Gascoyne Platform, where it thickens to the northwest to a maximum known thickness of 496 m in Yaringa 1. Conformably overlying the Kopke Sandstone is the Sweeney Mia Formation, which consists of oxidized, mixed carbonate and siliciclastic rocks with minor evaporitic beds, deposited in reducing, shallow lagoonal to supratidal environments. The formation has been positively identified in just five wells in the central part of the Gascoyne Platform (Edaggee 1, Hamelin 1 and 2, Yaringa 1, and Yaringa East 1), with a maximum known thickness of 192 m. It is probably present in Mooka 1, also in the central part of the Gascoyne Platform (Appendix 1).

Middle Devonian – Lower Carboniferous

A mid-Devonian hiatus separates the Lower Devonian section from a virtually continuous Middle Devonian – Lower Carboniferous succession, which extends across the northern part of the Merlinleigh Sub-basin and partially into the northern Gascoyne Platform (Fig. 3). The youngest unit from this succession on the Gascoyne Platform is upper Famennian in Carlston 1, although a Lower Carboniferous section is inferred from seismic data (Iasky et al., 2003). In the Merlinleigh Sub-basin the succession continues without a discernible break to the late Visean (Early Carboniferous).

The Nannyarra Sandstone is the product of a major marine transgression that possibly commenced as early as the late Emsian (late Early Devonian). Older ages (late Emsian to early Eifelian) from near the southern limit of the unit on the Gascoyne Platform (in Mooka 1) probably reflect progressive onlap of the unit to the east rather than progradation to the north, given that it pinches out to the south. The unit is unconformable on Lower Devonian or older rocks, and an angular relationship with the underlying Dirk Hartog Group is indicated by well data, although this cannot be seen on existing seismic sections. The unit is predominantly sandstone, with minor amounts of siltstone, and was deposited in low-energy, shallow-marine to intertidal environments. It is widespread in the northern Gascoyne Platform, with a maximum thickness of 190 m in Quobba 1. The sandstone thins to the south and progressively oversteps older units (Iasky and Mory, 1999). Along the eastern margin of the Merlinleigh Sub-basin, the Nannyarra Sandstone unconformably rests on granitic basement. Lithologically, the Nannyarra Sandstone grades into interbedded carbonate and siltstone of the overlying Gneudna Formation. This formation was deposited in a nearshore to restricted shallow-marine environment, and has a maximum known thickness of 1092 m in Quobba 1. Gypsum veins in Gneudna 1 imply locally evaporitic conditions. A massive, dolomitic unit (Point Maud Member) within the formation has its thickest known section (331 m) in Barrabiddy 1A (Gorter et al., 1998; Mory and Yasin, 1999). The Munabia Formation conformably overlies or interfingers with the Gneudna Formation, and consists of sandstone with minor amounts of claystone, conglomerate, and dolomite, deposited in a barrier complex (Hocking, 2000) during the Frasnian. In outcrop the unit is overlain by conglomerate and sandstone (Willaraddie Formation) of probably latest Devonian to earliest Carboniferous age deposited in an alluvial-fan environment (Hocking, 2000), implying a limited extent for this facies.

The Lower Carboniferous succession outcrops along the eastern margin of the Merlinleigh Sub-basin, where it consists of basal limestone (Moogooree Limestone) deposited in shallow-marine conditions, overlain by conglomerate, sandstone, and siltstone alluvial-fan facies (Williambury Formation), and sandstone and limestone that accumulated in shallow-marine conditions (Yindagindy Formation). On the eastern margin of the sub-basin the upper two units are equivalent to siltstone and sandstone of the Quail Formation — a likely shoreface to marine-shelf deposit (Hocking et al., 1987). The presence of the Lower Carboniferous succession in the Gascoyne Platform is inferred from seismic data, but has yet to be confirmed by drilling (Iasky et al., 2003).

Mid-Carboniferous – Permian

The mid-Carboniferous – Permian succession extends throughout the Merlinleigh, Byro, and Coolcalalaya Sub-basins, and the northernmost part of the Gascoyne Platform. It consists predominantly of Namurian–Tastubian (mid-Carboniferous – Lower Permian) mixed siliciclastic facies deposited in a glacially influenced marine environment (Lyons Group), overlain by abundantly fossiliferous Sterlitamakian–Aktastinian shale and limestone (Callytharra Formation), Baigendzhinian sandstone with minor amounts of shale and coal (Wooramel Group), and Kungurian–Ufimian interbedded sandstone and shale (Byro and Kennedy Groups; Hocking et al., 1987; Mory and Backhouse, 1997). Later Permian deposits are absent from the Southern Carnarvon Basin, but are present in the Peedamullah Shelf to the north (Mory and Backhouse, 1997; Crostella et al., 2000).

In outcrop the Lyons Group is clearly glacial marine in origin, and spans several glacial episodes. The group is largely undivided stratigraphically, as Hocking et al. (1987) considered that Condon's (1954) formations had little regional significance. Warroora 1 was terminated within the group after it penetrated 1483 m of Namurian–Stephanian (Carboniferous) shale and sandstone. The Permian part of the unit has been removed by erosion at that location, but a complete section including Lower Permian strata was intersected in Remarkable Hill 1 (1457 m) based on the ages determined by Mory and Backhouse (1997). The younger ages in Remarkable Hill 1 imply that this unit decreased in thickness to the north prior to erosion of the Warroora 1 section. In the Merlinleigh Sub-basin the Harris Sandstone at the base of the group — the only one of Condon's (1954) formations that Hocking et al. (1987) considered valid — is Stephanian–Tastubian (latest Carboniferous – Early Permian) in age. In this area the group is up to 3000 m thick, implying an average rate of deposition of over 30 m/m.y. (Iasky et al., 1998a, based on ages given by Mory and Backhouse, 1997), which Eyles et al. (2002) and Eyles et al. (2003) interpreted as an 'under-filled' phase of synrift subsidence with high relative sea levels. East of the Wandagee Ridge the group is thicker on the downthrown sides of major down-to-the-east faults, suggesting that rifting immediately preceded deposition.

In contrast to the glacially influenced Lyons Group, the conformably overlying Callytharra Formation has a rate of deposition of less than 2 m/m.y., based on the age range determined by Mory and Backhouse (1997). In the Byro Sub-basin and the southern Merlinleigh Sub-basin (Jimba Jimba area) the Callytharra Formation contains sandstone facies, indicating local fluviodeltaic incursions (Winnemia and Ballythanna Sandstone Members of Mory and Backhouse, 1997; equivalent to the 'Nunnery Sandstone' of Konecki et al., 1958). In the northern Merlinleigh Sub-basin the Cordalia Formation at the base of the Wooramel Group is in part laterally equivalent to the Callytharra Formation, and represents a lower deltaic to prodeltaic depositional system.

The Wooramel Group consists predominantly of fluvial- to marine-deltaic sandstone facies (Hocking et al., 1987). In the northern Merlinleigh Sub-basin the fine-grained, locally silty Cordalia Formation represents the basal unit of the group and passes upward into the fluvial-deltaic Moogooloo Sandstone. These two formations represent a single phase of deltaic progradation. The conformably overlying, generally finer grained Billidee Formation, which consists of carbonaceous shale and fine- to coarse-grained sandstone with minor amounts of conglomerate, was deposited in a weaker second phase of deltaic progradation into a shallow-marine environment (Hocking, 2000). The group is thickest in the northwestern part of the sub-basin where the maximum thickness recorded is 380 m in Quail 1.

The Byro Group conformably overlies the Wooramel Group and consists of alternating carbonaceous siltstone and mudstone, and fine-grained, commonly bioturbated sandstone. The seven formations within the group and the Coolkilya Sandstone of the overlying Kennedy Group form four coarsening-upward cycles: Coyrie Formation – Mallens Sandstone at the base; Bulgadoo Shale – Cundlego Formation; Quinnanie Shale – Wandagee Formation – Nalbia Sandstone; and Baker Formation – Coolkilya Sandstone at the top. The Byro Group is about 1500 m thick in outcrop, and the only complete well section is in Kennedy Range 1 (519–1882 m; Lehmann, 1967). The group falls entirely within the *P. sinuosus* Zone of Kungurian age, indicating rapid deposition (greater than 300 m/m.y.; Iasky et al., 1998a) on a storm-dominated marine shelf (Moore and Hocking, 1983). Foraminifera from the Quinnanie Shale indicate hyposaline conditions during deposition within a high-latitude interior sea (Haig, in press).

The Kennedy Group (comprising the Coolkilya Sandstone, Mungadan Sandstone, and Binthalya Formation) is exposed only in the Merlinleigh Sub-basin, and appears to be largely restricted to the Ufimian (early Late Permian). The group conformably overlies the Byro Group and contains similar siliciclastic facies, indicating a marine-shelf environment. Moore et al. (1980) proposed two depositional models for the Kennedy Group: a moderate palaeoslope model with a narrow transition between shoreface and offshore environments corresponding to the Coolkilya Sandstone; and a broad sandy shelf with a low palaeoslope corresponding to the Mungadan Sandstone and Binthalya Formation. Hocking (2000) considered that the Mungadan Sandstone represented renewed deltaic progradation in a subaqueous, fluvially dominated setting, in contrast to the more distal setting proposed by Moore et al. (1980). In a sequence stratigraphic interpretation of cyclicity within the group, Lever (2002) recognized 12 informal units and proposed changes in relative sea level between outer-shelf and tidal environments. Farther north the group was identified in the Peedamullah Shelf (Mory and Backhouse, 1997), but the use of 'Kennedy Group' may be inappropriate there as the succession is much younger, extending into the Midian, or higher in the Upper Permian.

Triassic

A Triassic succession has been intersected in Livet 1 and Wittecarra 1 (Crostella, 2001) above the mid- to Late Permian unconformity on the eastern margin of the Abrolhos Sub-basin. The units penetrated in these two wells include the Wittecarra Sandstone (base), Kockatea Shale, Woodada Formation, and Lesueur Sandstone (top), and are considered part of the northern Perth Basin succession. The Kockatea Shale extends into the southern Gascoyne Platform, where, on seismic data, it appears to be mostly flat lying (Iasky et al., 2003). The unit is present in the coastal cliffs south of Kalbarri at Shell House, where it conformably overlies the 11 m-thick type section of the Wittecarra Sandstone, which in turn overlies the Tumblagooda Sandstone (Hocking, 2000).

Jurassic

The only confirmed Jurassic sedimentary unit in the Southern Carnarvon Basin is the Lower Jurassic Woodleigh Formation — an interbedded shale and sandstone unit of lacustrine origin that is restricted to the central 50 km of the Woodleigh impact structure (Iasky and Mory, 1999; Mory et al., 2000; Iasky et al, 2001). Apatite fission-track analyses (AFTA) of the formation imply an original thickness of about 1100 m, before uplift and erosion, associated with breakup, removed about 700 m (Gibson et al., 2000).

Reported mid-Jurassic bivalves from an 'algal sandstone' near the Minilya River on Wandagee Station by Teichert (1940) have not been confirmed. The conspicuously glauconitic outcrop was mapped by Hocking et al. (1985) as Birdrong Sandstone, and considered as Cretaceous by Mory and Yasin (1999).

At least 22 alkali picrite diatremes and sills of Middle–Late Jurassic age intrude the Permian Byro Group east of the Wandagee Ridge (Jaques et al., 1986).

Cretaceous

The Cretaceous succession consists of the Winning Group (base), Haycock Marl, Toolonga Calcilutite, Korojon Calcarenite, and Miria Formation (top), and extends beyond the Gascoyne Platform along most of the North West Shelf, but only onto the western part of the Merlinleigh Sub-basin. The unconformity separating the Cretaceous succession from older rocks marks the breakup of Australia's western margin from Greater India in the Early Cretaceous. The average thickness of the Cretaceous succession in the Southern Carnarvon Basin is about 300 m, with thickening to the north towards the Exmouth Sub-basin and Peedamullah Shelf. A local Cretaceous trough lies immediately west of Dirk Hartog Island, from which the succession thins to the northwest onto the Bernier Ridge (Iasky et al., 2003).

The Winning Group records a widespread transgression over the Carnarvon Basin that spanned most of the Early Cretaceous. The group consists of a basal sand facies (Birdrong Sandstone) deposited in shoreface and nearshore environments, overlain by low-energy offshore-marine shale (Muderong Shale), then by low-energy, marine, silica-rich, fine-grained clastic rocks (Windalia Radiolarite), and glauconitic mudstone (Gearle Siltstone or Alinga Formation). The most prominent sequence boundaries within the Winning Group are at the tops of the upper Barremian to lower Aptian Muderong Shale, and mid- to upper Aptian Windalia Radiolarite (Mory and Yasin, 1999; Westphal and Aigner, 1997). Locally there is a break of up to 15 m.y. within the Albian to Cenomanian Gearle Siltstone (Dixon et al., 2003a). Turonian marine carbonaceous clay and bioturbated calcilutite (Haycock Marl) overlie the Winning Group with a minor break. This unit was previously placed in the 'Beedagong Shale' (Shafik, 1990), but that unit is considered invalid as it also includes some Campanian carbonate strata more appropriately assigned to the Toolonga Calcilutite (Dixon et al., 2003a). Isopachs for the Albian–Turonian section show considerable thickening to the northwest across the Rough Range Fault System (Iasky et al., 2003).

The Toolonga Calcilutite is widespread on the Gascoyne Platform, and disconformably overlies the Winning Group. The unit consists of fossiliferous calcilutite and calcisiltite deposited in a low-energy, inner- to middle-shelf marine environment. Isopachs for the unit show a depocentre across Shark Bay with a maximum thickness of over 300 m (Iasky et al., 2003). The unit thins to the east towards the Wandagee and Ajana Ridges, on and east of which it has been removed by erosion. In the northern Gascoyne Platform, the Toolonga Calcilutite grades laterally and upward into the Korojon Calcarenite. This unit consists of silty calcarenite and calcisiltite, and was deposited in a moderate-energy environment farther inshore than that of the Toolonga Calcilutite. The maximum known thickness for the unit is 80 m in Quobba 1. The Miria Formation disconformably overlies the Korojon Calcarenite and Toolonga Calcilutite in the northern Gascoyne Platform, and consists of calcarenite and calcisiltite deposited in a low- to medium-energy, marine-shelf environment. The formation ranges in thickness from 0.6 to 2.1 m in outcrop (Hocking et al., 1987) to 95 m in Airey Hill 1. In outcrop the unit is a condensed sequence marking the close of Cretaceous deposition.

Cainozoic

The Cainozoic succession in the Gascoyne Platform is dominated by flat-lying shallow-marine carbonate strata (Cardabia and Giralia Calcarenites, and Trealla Limestone of the Cape Range Group; Hocking et al., 1987), with minor siliciclastic rocks on the Gascoyne Platform (Miocene Lamont Sandstone) and Merlinleigh Sub-basin (Eocene Merlinleigh Sandstone and Miocene Pindilya Formation). On seismic sections from the western margin of the Gascoyne Platform the carbonate succession is interpreted as a trailing margin wedge (Iasky et al., 2003, plate 10). The Paleocene – Lower Eocene Cardabia Calcarenite disconformably overlies Cretaceous rocks, and outcrops in the Giralia, Marrilla, Chargoo, Warroora, and Gnargoo Anticlines. The maximum thickness of the unit is 77 m at Toothawarra Creek (Condon et al., 1956), but it does not extend far inland (Hocking et al., 1987). The Middle–Upper Eocene Giralia Calcarenite lies disconformably on the Cardabia Calcarenite and is preserved mainly offshore, where the maximum known thickness is 78 m in Edel 1 (Ocean Ventures Pty Ltd, 1972). Onshore, the Giralia Calcarenite is exposed in the Giralia and Marrilla Anticlines and near the eastern side of Hamelin Pool, and it appears to grade laterally into the Robe Pisolite in the Robe Embayment in the southeastern Northern Carnarvon Basin. Siliceous and ferruginous duricrust, calcrete, eolian sand, sheetwash, and alluvial deposits formed onshore during alternating arid and humid phases throughout the Cainozoic (van de Graaff et al., 1977; Hocking et al., 1987). These deposits are difficult to date except where fossiliferous units are intercalated — only their relative ages can be determined from field relationships.

Structure

Merlinleigh and Byro Sub-basins

The main part of the Merlinleigh Sub-basin is an elongate asymmetric half graben formed by west-southwesterly extension. It contains dominantly Upper Carboniferous to Permian sedimentary fill, which thickens to the west towards the north-trending, en echelon Wandagee and Kennedy Range Fault Systems (Iasky et al., 1998). Basement rises gently eastward, with a regional dip of 8° towards the margin of the basin, along which Devonian or Upper Carboniferous – Lower Permian strata unconformably overlie basement rocks. The Merlinleigh Sub-basin extends to the northwest to the Rough Range Fault, and shallows to the north towards the Marrilla High and Yanrey Ridge. Crostella and Iasky (1997) suggested that the Wandagee and Yanrey Ridges probably formed a contiguous feature prior to the mid-Carboniferous, even though gravity data show a small discontinuity between them.

Generally, strata in the Merlinleigh and Byro Sub-basins have steeper dips than strata in the Gascoyne Platform to the west, and folds and faults are more common. This may be a function of the basement fabric east of the Wandagee and Ajana Ridges, which has acted as the loci for mid-Carboniferous – Permian rifting and subsequent reactivation of faults. Since the orientation of these sub-basins does not match structural orientations in the Gascoyne Complex to the east, or the Carrandibby Inlier, basement below most of the Merlinleigh and Byro Sub-basins may belong to the Pinjarra Orogen.

The geometry of the northerly trending, en echelon, Wandagee and Kennedy Range Fault Systems is typical of growth faults associated with rifting (Lowell, 1985; Tearpock and Bischke, 1991; Withjack et al., 1995). However, although the Lyons Group increases in thickness across these faults, the older age of the base of the group in Warroora 1 compared to outcrop farther east implies that the faulting pre-dated Late Carboniferous deposition. The Late Carboniferous – Early Permian rift geometry probably controlled subsequent reactivation of major faults, possibly in the Late Permian (Warris, 1994), but more probably in the Early Cretaceous and Miocene (Hocking et al., 1987; Crostella, 1995a; Crostella and Iasky, 1997). Anticlinal features associated with the Wandagee and Kennedy Range Fault Systems include those tested by Quail 1, Gascoyne 1, and Burna 1, and are clearly post-Permian (Crostella, 1995a). As in the Perth Basin, breakup generated significant strike-slip movements along northerly trending faults (Mory and Iasky, 1996). Minor normal Miocene movements on these faults are inferred by the northerly compressional stress field for that time (Dentith et al., 1993; Harris, 1994) and offsets in Cretaceous strata.

Isopach maps for the Lower Permian section (Iasky et al., 2003, figs 7–9; Eyles et al., 2003) indicate downwarping along the west of the sub-basin during or just prior to deposition of the Lyons Group in the Late Carboniferous to Early Permian. They also indicate that the overlying Callytharra Formation was deposited in a period of quiescence. The deltaic Wooramel Group represents a period of sediment oversupply during which the rate of deposition was considerably less than that for the overlying Byro Group (greater than 300 m/m.y.; Mory and Backhouse, 1997), implying associated tectonism in the late Early Permian.

As there is no record of Kungurian (early Late Permian) to Valanginian (Early Cretaceous) deposition, the major uplift and erosion of the Merlinleigh and Byro Sub-basins cannot be dated directly. The major event along the entire western margin of Australia is the Late Jurassic – Early Cretaceous separation of Australia from Greater India, so significant tectonism should have affected the Southern Carnarvon Basin at this time. The structure of the region was also probably influenced by Late Permian deformation as seen in the northern Perth Basin (Iasky et al., 2003). The main structures formed by transtensional movements attributed to breakup are northerly oriented anticlines along the western margin of the sub-basin, such as the Quail Anticline, and northwesterly oriented faults, such as the Cardabia Transfer Fault (Crostella and Iasky, 1997).

With the convergence of Australia with the Eurasian Plate along the Banda Arc in the mid-Cretaceous, the tectonic regime of the Australian Plate switched from extensional to compressional (Veevers, 1991). Maximum compression over the Australian Plate has remained mostly in a north–south direction since then (Harris, 1994), although changes to this direction may have resulted from the rotation of the Australian Plate. In the Merlinleigh Sub-basin, major faults were reactivated with reverse movement, probably in the Miocene, comparable to reverse faulting along the Cape Range, Rough Range, and Giralia Anticlines (Hocking et al., 1987; Malcolm et al., 1991; Crostella, 1995a, 1996, 1997). During this period the prevailing north–south maximum shortening direction implies significant dextral strike-slip movement along northeasterly orientated faults, as in the Giralia area, and predominantly normal movement along northerly oriented faults (Iasky et al., 1998a). Miocene deformation in the southern Merlinleigh Sub-basin and the Byro Sub-basin is difficult to demonstrate as Cretaceous strata are restricted to the western margin of the Merlinleigh Sub-basin and are absent in the Byro Sub-basin. Minor Quaternary movements in the area were possibly associated with the Meeberrie Fault on the eastern side of the Byro Sub-basin, as shown by the Meeberrie earthquake in 1941 (Everingham, 1968).

Gascoyne Platform

Seismic and gravity data show that the diamond-shaped Gascoyne Platform is less deformed than surrounding sub-basins, and contains a main northerly trending, elongate trough that shallows abruptly to the east and south, and gradually to the west and north (Iasky et al., 2003). The Wandagee and Ajana Ridges form the easternmost part of the platform. Associated prominent gravity (Fig. 4) and magnetic highs (Fig. 5) imply that the ridge corresponds to a basement feature that was reactivated several times during the Phanerozoic. Apatite fission-track analyses

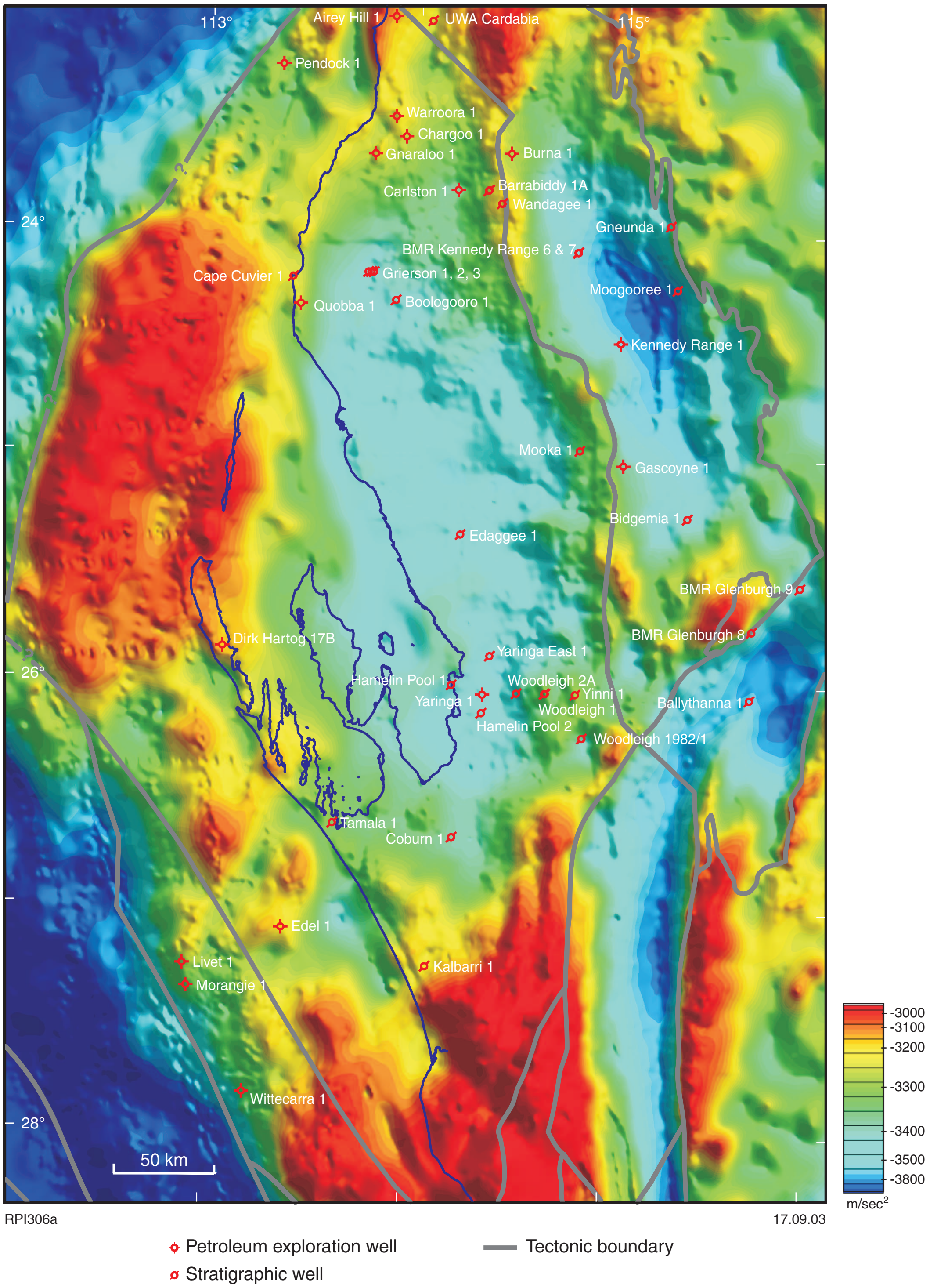

Figure 4. Isostatic residual gravity image, Southern Carnarvon Basin (from Lockwood and D'Ercole, in prep.)

(Gibson et al., 1998) indicate that three main periods of tectonism affected the platform: Late Carboniferous – Early Permian, Late Jurassic, and Miocene (Crostella and Iasky, 1997; Iasky et al., 1998b, 2003; Iasky and Mory, 1999). The Late Jurassic rifting that culminated with the breakup of Australia from Greater India in the Early Cretaceous is easily recognizable on seismic data as the base Cretaceous (breakup) unconformity. The Miocene compressional event is also clearly evident from reactivated major faults and associated anticlines throughout the platform (Iasky and Mory, 1999; Iasky et al., 2003).

The distinct mid- to Late Permian unconformity related to a rifting event in the northern Perth Basin can also be seen in the offshore southern Gascoyne Platform, and possibly also affected the remainder of the Southern Carnarvon Basin. The pre-Cretaceous succession pre-dates

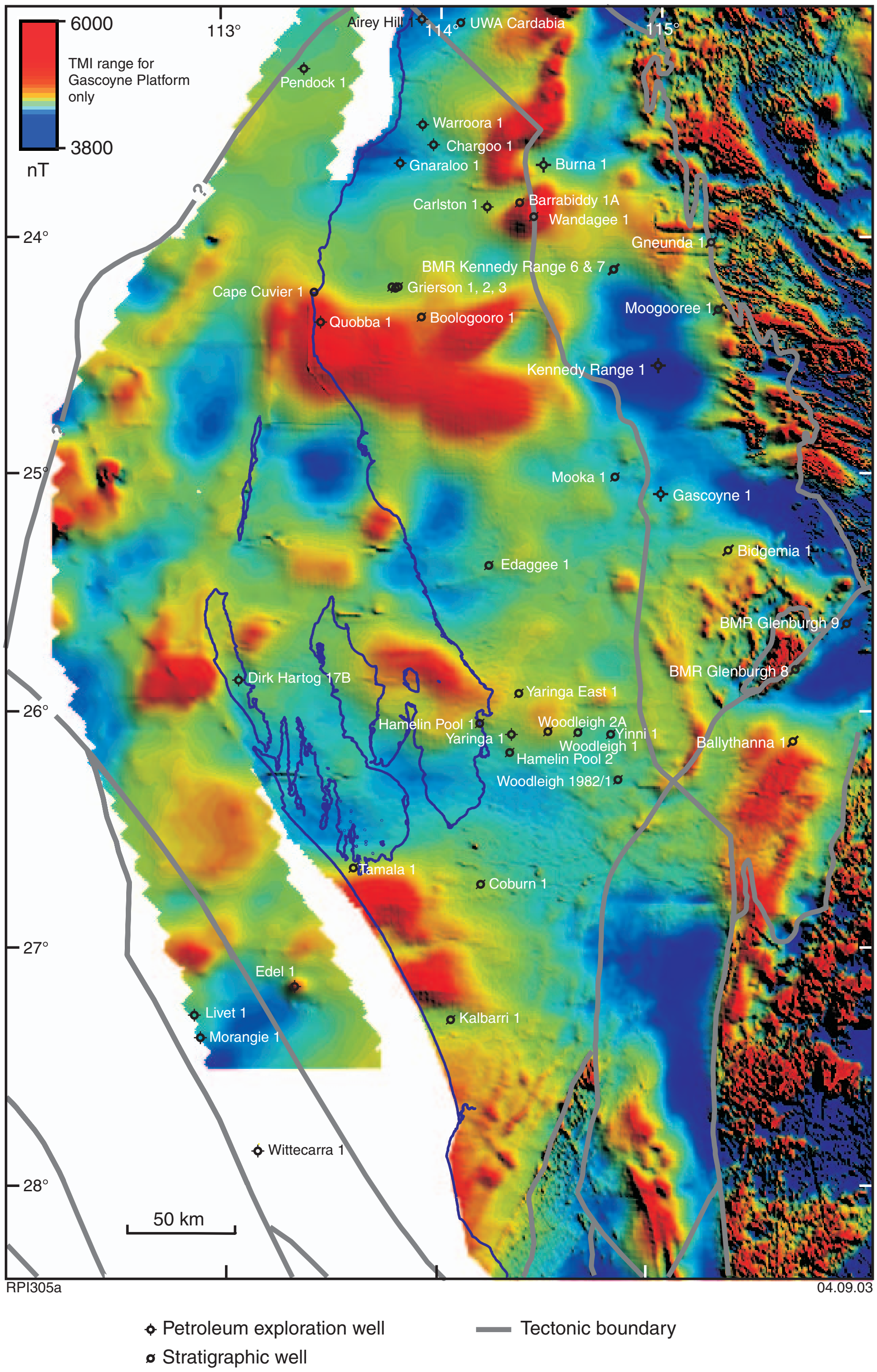

Figure 5. Total magnetic intensity (reduced to pole) image, Southern Carnarvon Basin

this event on the northern Gascoyne Platform, and the base Cretaceous unconformity was probably superimposed on the older unconformity. Therefore, faulting in the pre-Cretaceous succession could be either mid- to Late Permian or Late Jurassic, or both (Iasky et al., 2003).

Thermal maturity data from the Palaeozoic succession indicate low levels of maturity throughout the platform (Mory et al., 1998b; Ghori, 1998a). This suggests that it was never buried as deeply as the Merlinleigh Sub-basin to the east, and was a positive structural feature for most of the mid-Carboniferous through to the earliest Cretaceous. Thermal maturity data from below the Cretaceous section are relatively uniform across the platform. Modelling of these data show that Devonian and older rocks reached maximum burial in the Late Carboniferous – Early Permian, and that about 1300 m of strata were removed from the Gascoyne Platform during the main rifting episodes (Ghori, 1999). Along the platform, the Ordovician–Devonian succession is thicker in the south, and the stratigraphy below the Cretaceous transgressive cycle becomes progressively younger to the north. This indicates that the focus of early deposition shifted from the southern Gascoyne Platform in the Early Palaeozoic to the north from the Late Devonian onwards, and was followed by relatively uniform erosion across the platform.

Bernier Ridge

Below the Cretaceous succession, uplifted crystalline basement (Bernier Platform of Geary, 1970; Symonds and Cameron, 1977; Bernier Ridge of Lockwood and D'Ercole, in prep.) is interpreted from seismic and gravity data in the northern offshore part of the Gascoyne Platform. The eastern margin of the ridge is faulted against Palaeozoic strata, whereas a gradual rise in basement, with minor down-to-the-west faults, is evident along its western side (Iasky et al., 2003). Devonian and older rocks appear to be eroded on the eastern side of the basement high, and there is no indication of thinning or thickening of strata towards the faulted contact, so a post-Devonian and pre-Cretaceous age is indicated for this uplift. The most likely time for this basement uplift was between the mid-Carboniferous and Late Permian, based on the formation of major depocentres of this age in the northern Perth Basin and eastern Southern Carnarvon Basin, and the presence of Upper Permian – Lower Triassic intrusive rocks in Edel 1 (Le Maitre, 1972). Another feature of the Bernier Ridge is that the Cretaceous section is thicker to the east, implying that syndepositional normal movement continued after breakup on some of the faults associated with this basement uplift (Iasky et al., 2003).

Woodleigh impact structure

The Woodleigh impact structure lies largely within the Gascoyne Platform, with its centre about 50 km east of Hamelin Pool at latitude 26°03'25"S, longitude 114°39'50"E. An impact origin is indicated by the central uplifted granitoid core, which in Woodleigh 1 displays shock-induced planar deformation features (PDFs) in quartz, pervasive diaplectic vitrification of feldspar, and penetrative pseudotachylite veining (Mory et al., 2000, 2001; Koeberl et al., 2001; Hough et al., 2001). The structure is covered by up to 600 m of Jurassic–Cainozoic sedimentary rocks, so the estimated diameter of 120 km is based on gravity and magnetic data (Iasky et al., 2001). Suggestions that the structure is smaller, based on empirical morphometric ratios (Reimold and Koeberl, 2000; Renne et al., 2002), excluded the sedimentary collar as part of the central uplift, even though Therriault et al. (1997) indicated this collar should be included. Shock pressures of 16.6 to 20.2 GPa calculated from PDFs suggest structural uplift of about 6.3 km (Whitehead et al., 2003), implying a diameter of about 60 km. However, such empirical calculations only provide an order of magnitude guide to crater size.

A Late Devonian age close to the Frasnian–Famennian boundary was deduced for the impact from K–Ar analyses of illitic clays from the central shock-metamorphosed granitoid basement and reworked material from the base of Jurassic lacustrine fill (Uysal et al., 2001, 2002), and has been confirmed from Rb–Sr isochrons (Uysal, I. T., 2003, written comm.). This is towards the base of the possible age range deduced from the regional stratigraphy (Middle Devonian to Lower Jurassic), although ejecta have yet to be identified.

Imaging of gravity data shows a multi-ring structure with an inner-ring anomaly about 25 km in diameter (Iasky et al., 2001). An interpretation of seismic data indicates a diameter of about 31 km for the uplifted central dome (including the central basement area and the sedimentary collar) below the Cretaceous section, compared to about 37 km near basement (Uysal et al., 2002). There is good coincidence between the concentric annular gravity lows and highs, and the troughs and ridges on the limited seismic data. The outermost diameter corresponds to the abrupt truncation of the northerly trending Wandagee and Ajana Ridges, and coincides with an arcuate magnetic anomaly and a drainage divide, implying recent reactivation along a bounding ring fault. The southeast–northwest asymmetry of gravity anomalies within the structure is interpreted as the combined effect of different rock types within the impact site and post-impact tilting of the platform. Reactivation of faults along the Wandagee and Ajana Ridges probably produced a regional tilt to the northwest, which would account for the removal of the melt sheet and the east–west asymmetry evident on gravity images. Seismic data show intense deformation up to 25 km from the centre and only minor deformation to the outer rim. This pattern of deformation is consistent with other impact structures, in that the inner third to half has undergone the most intense deformation (Iasky et al., 2001).

Geological evolution

?Cambrian – Early Devonian

The three redbed–carbonate cycles within this 100 m.y. interval represent an intracratonic phase of basin development (Fig. 6a). The first cycle is poorly known from Wandagee 1 (and possibly also in Quail 1), and is probably Late Cambrian to Early Ordovician in age. This cycle may correlate with the section identified from seismic data in the southwestern offshore part of the Gascoyne Platform. The second cycle is probably Late Ordovician to latest Silurian in age, and is well known from outcrop and petroleum exploration wells in the Gascoyne Platform. There is no unambiguous evidence of mid-Ordovician to Early Devonian deposition in the Merlinleigh or Byro Sub-basins, as the succession, if present, lies below up to 5 km of Carboniferous–Permian strata. However, the Tumblagooda Sandstone outcrops along the southwestern margin of the contiguous Coolcalalaya Sub-basin. The third cycle is Early Devonian in age, and has a thin carbonate unit at its base. It is known with certainty only from the central part of the onshore Gascoyne Platform. Apart from the angular relationship between the first two cycles, indicating growth on a pre-

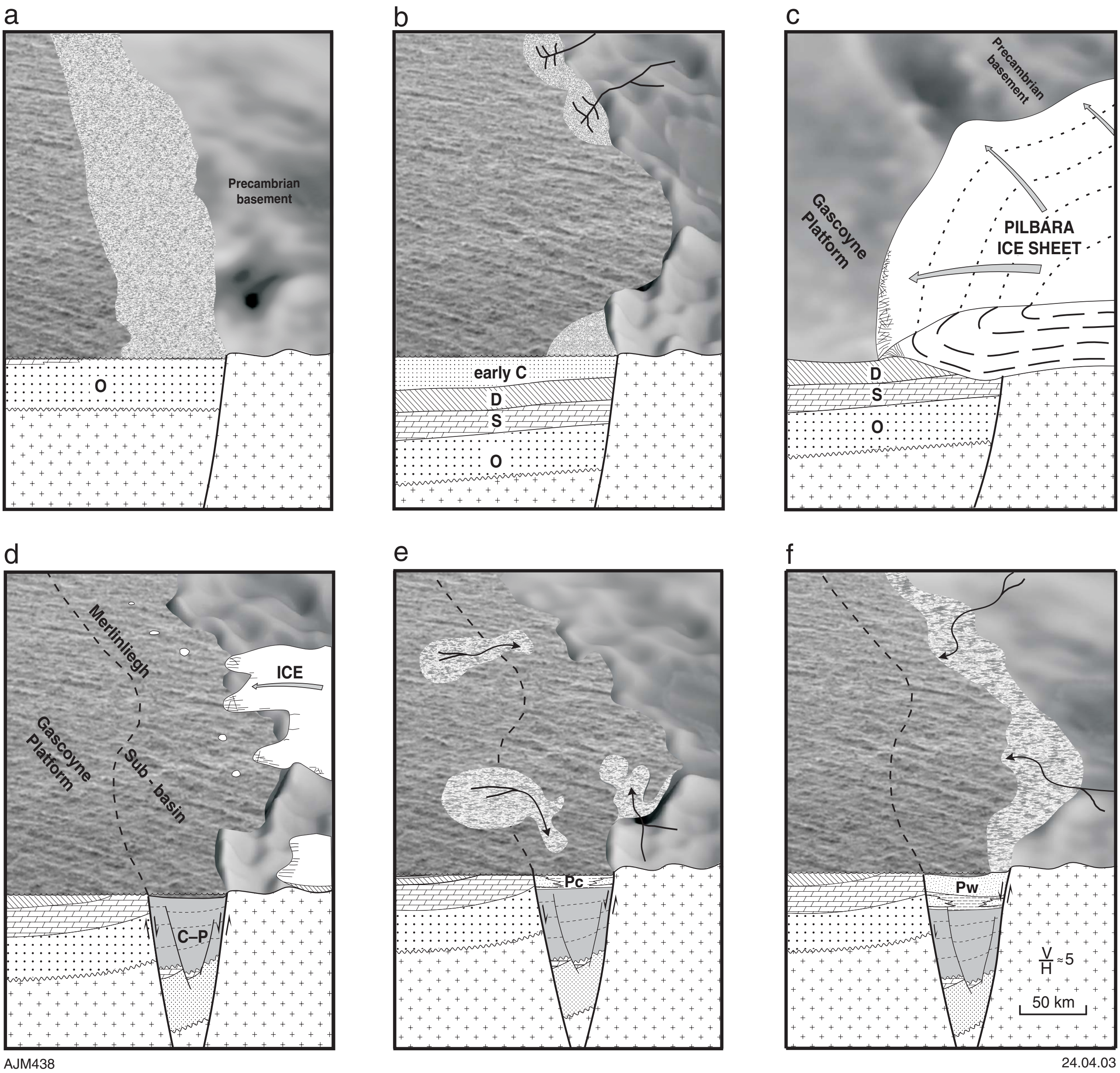

Figure 6. Palaeozoic palaeogeographic evolution of the Southern Carnarvon Basin: a) Late Ordovician – Early Silurian, b) Early Carboniferous, c) mid-Carboniferous, d) Tastubian (Early Permian), e) Aktastinian (Early Permian), f) Baigendzhinian (Early Permian). O = Ordovician, S = Silurian, D = Devonian, C = Carboniferous, P = Permian, Pc = Callytharra Formation, Pw = Wooramel Group. Not to scale; approximate area covered is indicated in Figure 1 (after Eyles et al., 2003)

Tumblagooda Sandstone fault in the southwestern part of the platform (Iasky et al., 2003), there is no evidence of folding or faulting within this period. Similarly, AFTA data do not show any cooling events prior to the Carboniferous (Gibson et al., 1998, 2000; Ghori et al., in prep.).

The maturity of the Lower Ordovician section in Wandagee 1 is similar to that of the top of the mid-Silurian Yaringa Formation in Pendock 1, as shown by a conodont alteration index (CAI) of 1.5 – 2.0 (Nicoll and Gorter, 1995), and slightly greater than that of the Upper Devonian section in Barrabiddy 1A (CAI of 1.0 – 1.5; Mory and Yasin, 1999). In Pendock 1 that level is presently 1500 m deeper than the conodont fauna from Wandagee 1, and 1400 m deeper than the fauna from Barrabiddy 1A. The maturities of these sections and their present relative depths indicate that post-Devonian erosion removed slightly more than 1000 m of strata over the northern Gascoyne Platform (probably at breakup), and that no more than 200 m has been eroded from below the Devonian section in Wandagee 1. On this evidence, deposition over the Wandagee Ridge between the mid-Ordovician and mid-Devonian had little effect on the maturity of the Lower Ordovician section, implying that the ridge was a positive structural feature for most of this time compared to the remainder of the Gascoyne Platform.

A comparison of the Cambrian – Lower Devonian succession in the Southern Carnarvon Basin with that in the Canning Basin (Fig. 3) shows little in common, apart from the largely dolomitic sections of mid- to Late Silurian age (Coburn Formation and the upper part of the Sahara Formation). The correlation implies that depositional controls were local rather than continent wide, presumably related to tectonic events within and immediately adjacent to each basin.

Middle Devonian – Early Carboniferous

The Middle Devonian break in sedimentation appears to mark a period of minor erosion, with little evidence of structure within the basin. The Middle Devonian – Lower Carboniferous succession is preserved only in the northern part of the Merlinleigh Sub-basin, and partially in the adjacent Gascoyne Platform. Only minor differences in the Devonian part of this succession are evident between the two sub-basins (Fig. 3), implying that the Merlinleigh Sub-basin did not become a separate entity until the mid-Carboniferous. During this period, the Wandagee and Ajana Ridges, which are disrupted by the Late Devonian Woodleigh impact structure, as shown on the gravity image of the region (Fig. 4), were not positive structural features. To date, neither immediate post-impact crater fill (Famennian–Tournaisian), nor ejecta from this impact, has been found.

Correlation of this interval with the Canning Basin shows considerable similarities in facies. The only significant differences are that, within the Southern Carnarvon Basin, carbonate reefs are absent in the Famennian, and alluvial fan facies are present in the Visean (Fig. 3). The similarities carry into the Southern Bonaparte Basin (Mory and Dunn, 1990), implying that controls on deposition operated on a scale much larger than individual basins, and possibly related to global climate rather than basin tectonics or local seaways.

Late Carboniferous – Permian

Continental-scale glaciation had a distinct influence on sedimentation in the Late Carboniferous – Early Permian, but this time also coincided with the formation of a depocentre in which a section up to 5 km thick accumulated along the eastern margin of the basin (Merlinleigh, Byro, and Coolcalalaya Sub-basins). The Fitzroy Trough (Canning Basin) and the Petrel Sub-basin (Northern Bonaparte Basin) have a similar history, implying linked or continent-wide structural events at this time, although the timing of events recorded by the fill in these basins varies somewhat (Eyles et al., 2002). In central Australia, this period was at the end of the Alice Springs Orogeny, and relatively rigid cratonic plates may have transmitted this stress across the continent. In the Southern Carnarvon Basin, listric normal faulting associated with isostatic compensation and uplift of the flank of a failed rift probably pre-dated marine deposition. In keeping with the suggestion of Powell and Veevers (1987), Eyles (1993) shows that rift-related uplift across the high-latitude portions of Gondwana triggered regional ice covers during the Late Carboniferous, thereby implying that rifting and glaciation were intimately related (Figs 6c,d), and indicating why glacial coarse-grained clastic strata were the first deposits. Subsidence initially exceeded sediment influx, and the first phase of sedimentation (Lyons Group) shows a wide variety of mass-flow diamictites, poorly sorted conglomerates, and common deformation structures attributed to downslope slumping. By the late Sakmarian – early Artinskian the source areas were largely eroded, deposition rates declined as the basin expanded, and siltstone and carbonate (Callytharra Formation) accumulated in offshore settings (Fig. 6e). Continued slow rates of subsidence during a period of increased sediment influx in the late Artinskian resulted in the progradation of fluvial and deltaic wedges, and the accumulation of coarse-grained sand facies (Fig. 6f; Wooramel Group; Eyles et al., 2002).

Renewed Kungurian–Ufimian rapid deposition (Byro and Kennedy Groups) indicates renewed rifting-related subsidence, although, as with older deposits, palaeocurrent directions are dominantly north-northwesterly (Hocking et al., 1987), implying little input from the relatively elevated Gascoyne Platform to the west. The dominance of such palaeocurrents for the Kungurian–Ufimian is difficult to question, as outcrops of this age abut the bounding fault, but the paucity of older Permian outcrop along the western margin of the Merlinleigh Sub-basin has produced a bias in palaeocurrent data; easterly to northeasterly palaeocurrents, indicating erosion of the Gascoyne Platform at this time, are based on just a few outcrops. Other evidence for the lack of Late Carboniferous – Permian deposition over the Gascoyne Platform is the low thermal maturity of the Silurian section compared to the high maturity of the Devonian–Permian section in the western part of the Merlinleigh Sub-basin. El-Tabakh et al. (in press) speculated that the intense dolomitization of the Silurian Dirk Hartog Group is related to exposure of the Gascoyne Platform from this period until the end of the Jurassic.

Although uplift and associated erosion of the Gascoyne Platform was probably coincident with the mid-Carboniferous – Permian rift, and may explain the apparent lack of Upper Devonian fill in the Woodleigh impact structure, Late Permian tectonics are an alternative explanation. The Jurassic fill of the Woodleigh impact structure (containing reworked Early Permian palynomorphs) implies uplift and erosion of the region between the Early Permian and the Jurassic. Offshore, Late Permian tectonics and an associated unconformity are evident in the Abrolhos Sub-basin as well as along the margin of the Gascoyne Platform (Iasky et al., 2003). Deep intrusives below the platform are evident from aeromagnetic data (Fig. 5), and below Edel 1 from seismic and aeromagnetic data. In Edel 1, dykes and sills are dated as Late Permian to Early Triassic (Ocean Ventures Pty Ltd, 1972; Le Maitre, 1972) implying that at least some of the deep intrusive rocks are this age, and possibly explaining why sedimentation effectively ceased across the platform at about this time until the Early Cretaceous (Lockwood and D'Ercole, in prep.).

Triassic–Jurassic

The Triassic and Jurassic were periods of non-deposition across the Southern Carnarvon Basin, except where thin Triassic sediments encroached over the southern Gascoyne Platform along the depositional margin of the Perth Basin, and lacustrine sediments were deposited within the Woodleigh impact structure in the Early Jurassic. There seems to be no tectonic explanation why deposition of lacustrine sediments in the Woodleigh impact structure commenced at this time, and therefore older crater fill may be present. The predominantly northwesterly dip of Palaeozoic strata on the Gascoyne Platform, the east–west asymmetry of the Woodleigh impact structure, and the folding and faulting of the succession in the Permian depocentres pre-dates the Cretaceous. These features are probably related to Late Jurassic rifting and the subsequent separation of Australia from Greater India. Nevertheless, the Late Devonian age of the Woodleigh impact, and the paucity and lack of deformation of Triassic and Jurassic strata, imply prolonged tectonic quiescence for almost 160 m.y. in at least the southern onshore part of the Gascoyne Platform.

Rifting between Australia and Greater India began in the Middle Jurassic and culminated in breakup in the Early Cretaceous. Although its effect on the Gascoyne Platform was less than in regions to the north and south, the Late Jurassic cooling episode indicated from AFTA (Gibson et al., 1998) is probably related to erosion associated with these movements. Middle–Late Jurassic erosion over the Gascoyne Platform is estimated to be in the order of 500–700 m over the Woodleigh impact structure (Mory et al., 2001), and by analogy the 1500 m of pre-Cretaceous erosion estimated farther north on the platform is probably also this age. Major northerly trending faults, such as the Wandagee and Kennedy Range Faults, were reactivated at this time with significant dextral strike-slip movement, along with the development of northwesterly trending transfer faults, such as the Cardabia Transfer Fault (Crostella and Iasky, 1997; Iasky and Mory, 1999). In the Bernier Ridge the presence of basement rocks directly below Cretaceous strata is explained as rift-flank uplift near the end of the Jurassic (Lockwood and D'Ercole, in prep.).

Cretaceous–Cainozoic

Following breakup, a basal transgressive sand (Birdrong Sandstone) was deposited over the entire Gascoyne Platform and along the western part of the Permian depocentre, predominantly in coastal to inner-shelf environments. Overlying shallow-marine claystone, radiolarite, calcilutite, and calcarenite record progressively deeper waters across the platform. The Winning Group gradually thickens towards the northern part of the Gascoyne Platform, attaining its greatest thickness in the Exmouth Sub-basin of the Northern Carnarvon Basin. Apart from penecontemporaneous movement along the Rough Range Fault System, there is little evidence of Early to mid-Cretaceous tectonism within the Southern Carnarvon Basin. This is reflected in the dominance of fine-grained units of low-energy depositional style, rather than coarse-grained siliciclastic units generated by significant uplift and erosion of the hinterland.

A change in ocean currents and rates of sediment supply initiated a transition to carbonate deposition in the Turonian (Haycock Marl) that was virtually complete by the Coniacian in the Southern Carnarvon Basin. Carbonate deposition continued from the Late Cretaceous (Toolonga Calcilutite, Korojon Calcarenite, and Miria Formation) into the Cainozoic (Cardabia and Giralia Calcarenites, and Trealla Limestone). In the Late Cretaceous, the depocentre shifted from the northwestern side of the Rough Range Fault System to near Shark Bay (Iasky et al., 2003), but the reason for this change is unclear. Offshore, thick prograding carbonates were deposited throughout most of the Cainozoic, while the onshore part of the basin remained largely subaerial, with carbonate-dominated deposition in the Palaeocene, Eocene, and Miocene in the western onshore area (Hocking et al., 1987).

At the end of the Miocene a compressional tectonic episode reactivated pre-existing major faults, and created the 'salt marsh' anticlines, which appear to increase in amplitude to the north, and probably enhanced Late Jurassic – Early Cretaceous structures in the Merlinleigh and Byro Sub-basins. The elevation of Eocene marine deposits to about 220 m AHD in the Merlinleigh Sub-basin and at Kalbarri (Haig and Mory, in prep.), and a Cainozoic cooling event indicated by AFTA data (Gibson et al., 1998), are probably related to this compression.

After the Miocene phase of compression, a widespread calcrete duricrust formed in the Pliocene, and thick coastal dunes developed in the Pleistocene. This was followed by the deposition of a thin veneer of Quaternary continental sediments in an arid climate.

Petroleum potential

Source potential

Intervals with good- to excellent-quality source rocks have been identified in the Upper Silurian Coburn Formation, Upper Devonian Gneudna Formation, and Permian Wooramel and Byro Groups (Fig. 7; Ghori 1996, 1998a,b, 1999, 2002). For the Silurian and Devonian section, good to excellent source-rock characteristics have only been recorded from fully cored intervals, because source rocks within carbonate facies are generally thin and therefore difficult to discriminate in cuttings. Although shaly intervals within the more clastic parts of the Silurian and Devonian sections are easily identifiable, cuttings from such intervals have proven to be low in organic matter.

The best Silurian source intervals recognized to date are from the Coburn Formation (Dirk Hartog Group) in Yaringa East 1 (deepening), which show an organic richness of over 7% total organic carbon (TOC), a potential yield ($S_1 + S_2$) of up to 38 mg/g, and a hydrogen index of up to 505 (Ghori, 2002). Good source intervals from this formation are also recognized in Coburn 1 and Woodleigh 2A in the southern part of the Gascoyne Platform (Yasin and Mory, 1999a; Mory et al., 2001). Pyrolysis-gas chromatography and extract analyses

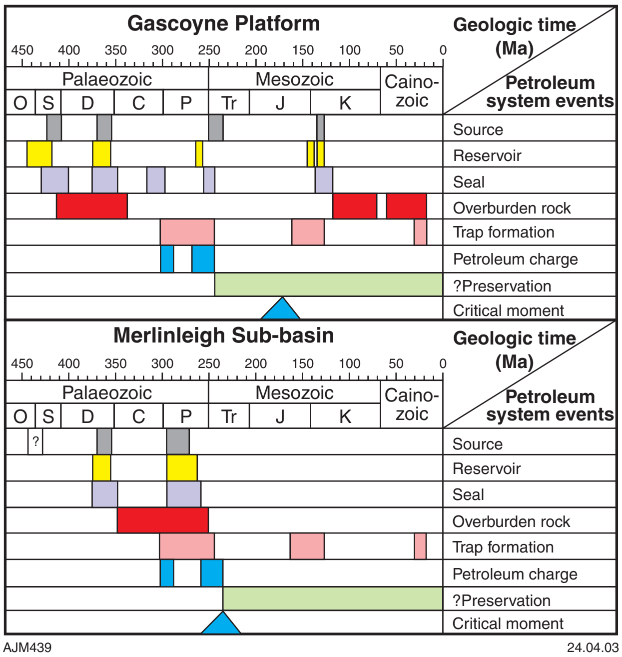

Figure 7. Likely petroleum systems in the Gascoyne Platform and Merlinleigh Sub-basin

confirm that these organic facies are oil prone and were deposited in reducing environments.

The best Devonian source-bed characteristics recorded are from the Gneudna Formation in Barrabiddy 1A on the Gascoyne Platform, with organic richness reaching 13.5% TOC, a potential yield of up to 40 mg/g, and hydrogen index of up to 267. In the Merlinleigh Sub-basin, good source beds are present in Gneudna 1 and Uranerz CDH 8 within the outcrop belt on the eastern margin of the sub-basin (Ghori, 1996).

The best Lower Permian source beds are present in the Artinskian Wooramel Group, which is widespread in the Merlinleigh, Byro, and Coolcalalaya Sub-basins. The first report on source beds of this age by Emmett (1981) has been confirmed by significant additional analyses (Ghori, 1996). The group is up to 380 m thick and contains interbedded organic-rich shales, with fair to very good source potential. The organic richness of analysed samples is up to 16% TOC, with an average of 7%, and they are predominantly gas generating. The potential yield is up to 12 mg/g, with an average yield of 6 mg/g. Within the Byro Group, good to fair, predominantly gas-generating source-rock intervals are present over a 700-m thick interval in Kennedy Range 1.

In the Perth Basin, the Lower Triassic Kockatea Shale is regarded as the major oil-source rock (Summons et al., 1995), and may provide a source for the long-range migration of hydrocarbons from the Abrolhos Sub-basin into the southwestern part of the platform. In the Abrolhos Sub-basin, the overlying Woodada Formation may supplement the Kockatea Shale as a source (Crostella, 2001), but again long-range migration is required. Similarly, long-range migration from Jurassic source rocks of the Northern Carnarvon Basin — considered amongst the most effective of the North West Shelf (Scott, 1992; Longley et al., 2002) — is possible, but unlikely as only small quantities of hydrocarbons of likely Jurassic origin (Partington et al., 2003) have been found along Rough Range. Mudstone facies in the Cretaceous Winning Group have generated hydrocarbons in the Northern Carnarvon Basin, and possibly biogenic gas on the Peedamullah Shelf (Crostella et al., 2000), but the unit is immature on the Gascoyne Platform and only can be considered as a source interval farther to the west.

Maturity

Within the Gascoyne Platform, the maturity of the Silurian Dirk Hartog Group increases northward, probably due to deeper burial. The increase is not dramatic as the depth to the top of the group varies from 568 m in Coburn 1 in the south, to 1850 m in Pendock 1390 km to the north. In Coburn 1, Woodleigh 2A, and Yaringa East 1 (deepening), the Silurian source-beds are immature to early mature for oil. To the northwest in Quobba 1 and Pendock 1, Silurian strata are within the peak oil-generative window. If the group is present in the Merlinleigh Sub-basin it is likely to be overmature, as conodonts from the Devonian section in Quail 1 show a conodont alteration index of 4 (Nicoll and Gorter, 1995), which is equivalent to a vitrinite reflectance of at least 2%Ro. However, Quail 1 may not be typical of the western Merlinleigh Sub-basin, as seismic and gravity data indicate that this area has undergone a higher level of deformation than elsewhere, implying that the geothermal gradient is abnormally high.

In the Merlinleigh Sub-basin, the Gneudna Formation varies from immature in outcrop along the eastern margin to overmature in Quail 1 on the western side of the sub-basin, adjacent to the Wandagee Ridge; however, maturity modelling shows that the unit is mostly mature to overmature across the sub-basin. On the Gascoyne Platform, the formation is mature in Barrabiddy 1A (276–778 m) and Pendock 1 (1030–1692 m), and decreases in maturity to the south and northeast towards the Peedamullah Shelf.

In the Merlinleigh Sub-basin, the Permian Wooramel Group is marginally mature in the northwest and immature in the south. The only exception is in Kennedy Range 1 where both vitrinite reflectance and Rock-Eval T_{max} indicate an abnormally high thermal maturity. In Kennedy Range 1, which was terminated within the Lyons Group at a total depth of 2227 m, there is an abrupt increase in the maturity below 1400 m within the middle of the Byro Group so that the section below this depth is mid-mature to overmature. This may have been caused by a nearby small intrusion, evident on magnetic data, although typically such intrusions usually only increase maturity within their immediate vicinity. The magnetic anomaly over this intrusion is of similar amplitude and frequency to anomalies on the northern Wandagee Ridge that correspond to kimberlitic pipes (Iasky et al., 1998a). In the southern Merlinleigh and Byro Sub-basins, Permian outcrop is mostly at an early mature stage, although a sample from the top of the Kennedy Group yielded a vitrinite reflectance of 0.43%Ro (Iasky et al., 1998a).

In the northern Merlinleigh Sub-basin, the Permian succession is comparatively more mature than in the outcrop belt to the southeast, and the base of the succession ranges from early mature to overmature. Burial by a now-eroded, thick Permian section is the most likely reason for the increased maturation, as the overlying Cretaceous–Cainozoic section is generally less than 1000 m thick.

Maturity modelling of Wittecarra 1 indicates that the rate of hydrocarbon generation of the Kockatea Shale peaked at the end of the Jurassic just prior to breakup, implying that long-range migration and the preservation of older structures are required to trap and retain such hydrocarbons within the Gascoyne Platform. For Silurian and Devonian source rocks, by comparison, major Permian erosion in geohistory models (Iasky et al., 2003; Ghori et al., in prep.) places the maximum rate of hydrocarbon generation at the end of the Permian. However, if the major erosion took place during the Early Cretaceous, the peak of hydrocarbon generation for these beds extends from the Permian to Middle Jurassic. Therefore, a successful petroleum system requires that structural traps formed before the Late Permian.

Reservoirs

The Ordovician Tumblagooda Sandstone has variable porosity and permeability, but porosity is typically good, even at depths greater than 1000 m. In the southern onshore part of the Gascoyne Platform the Tumblagooda Sandstone is a subartesian aquifer. By comparison, the overall porosity and permeability of the carbonate intervals within the Dirk Hartog Group is low, as it is extensively dolomitized, and replaced, in part, by late-stage anhydrite cement. Presumably, the carbonate intervals must have had considerably better permeability in the past to facilitate dolomitization (El-Tabakh et al., in press), although it is likely the dolomitization took place at shallow depths shortly after deposition. In contrast to the carbonate facies, thin sandstone beds near the base of the group have excellent reservoir characteristics. The Lower Devonian Kopke Sandstone and Middle Devonian Nannyarra Sandstone typically have good reservoir characteristics. The former is an excellent aquifer, with artesian flows near the coast in the central onshore Gascoyne Platform. In contrast to the older carbonate succession of the Dirk Hartog Group, dolomitization of the Point Maud Member within the Gneudna Formation appears to have enhanced the development of vuggy porosity and permeability (Mory and Yasin, 1999).

The primary reservoir objectives in the Merlinleigh Sub-basin are the Lower Permian Moogooloo Sandstone (Wooramel Group), and the Devonian Nannyarra Sandstone and Munabia Formation (Lavering, 1982; Percival and Cooney, 1985; Crostella, 1995a; Havord, 1998; Baker et al., 2000). Devonian limestone of the Gneudna Formation, sandstone of the Devonian Willaraddie Formation, Lower Carboniferous Williambury Formation, and Permian sandstone within the Lyons, Byro, and Kennedy Groups may be considered as secondary reservoir objectives. Although there have not been any specific petrographic studies carried out, sandstone of the Williambury Formation, Yindagindy Formation, and Harris Sandstone may have reasonable reservoir characteristics, but are unlikely to be regionally extensive.

Within the Cretaceous succession, the Birdrong Sandstone and the Windalia Sandstone Member of the Winning Group have excellent reservoir characteristics, and are proven reservoirs to the north (e.g. Tubridgi Gasfield, Crostella et al., 2000; Bunt et al., 2001; and Barrow Island, Ellis et al., 1999). The former unit is the dominant aquifer in the basin, with artesian flows near the coast.

Seals

There are several potential Palaeozoic sealing sections within the Gascoyne Platform (Fig. 7). Shale of the Marron Member, at the base of the Dirk Hartog Group, is up to 100 m thick and may seal the underlying Tumblagooda Sandstone, as well as sandstone beds within the member (Iasky and Mory, 1999). Intraformational shale beds and tight dolomite higher within the group and within the overlying Faure Formation also could act as seals, as long as fractures are closed. Thinly bedded dolomite and shale of the Sweeney Mia Formation is almost 200 m thick and locally is an aquiclude to the underlying Kopke Sandstone, thereby demonstrating potential as a sealing unit in the central part of the onshore Gascoyne Platform.

Shales up to 40 m thick within the Gneudna Formation could be an effective intraformational seal, as well as sealing the underlying Nannyarra Sandstone. The nature of the Lower Carboniferous succession in the Gascoyne Platform is uncertain, but in the Merlinleigh Sub-basin, limestone and shale beds of the Moogooree Limestone and Quail Formation could potentially seal the Munabia Formation. The Lyons Group is a thick, predominantly shaly unit that could seal underlying reservoirs and intraformational sandstones, but is absent over most of the Gascoyne Platform (Iasky and Mory, 1999). Sealing units are common throughout the remaining Permian section east of the Gascoyne Platform, especially in the laterally equivalent Callytharra and Cordalia Formations, which may seal the Lyons Group, and the Billidee and Coyrie Formations, which may seal the Moogooloo Sandstone. The Bulgadoo and Quinnanie Shales are additional possible sealing units in the upper part of the Byro Group.

The Muderong Shale is a proven seal in the Northern Carnarvon Basin (Crostella et al., 2000) and should also be an effective seal, where thick enough, in the Southern Carnarvon Basin.

Traps

The main objective for petroleum exploration in the Gascoyne Platform has been the Birdrong Sandstone, sealed by the Muderong Shale, in Miocene anticlinal structures on the hanging wall of pre-breakup normal faults reactivated with reverse movement. In the footwall, pre-Cretaceous strata commonly dip away from the controlling fault, and the trap would be fault dependent. In some instances Miocene faults were reactivated with normal movement, and form rollover plays on the footwall. Although such plays were targeted by early exploration, a few untested Miocene structures remain in the northern part of the area surrounding Pendock 1 (Iasky et al., 2003). A likely problem with the Birdrong Sandstone is that strong artesian flow could displace or wash hydrocarbons from all but the most robust traps unless such flow is diverted by pinchouts, low permeability, or faults.

Possible stratigraphic traps include incised channels filled by Birdrong Sandstone and sealed by the Muderong Shale. In the northern Gascoyne Platform there may be additional traps in which the Birdrong Sandstone is missing, thereby allowing the Muderong Shale to seal dipping Palaeozoic reservoir rocks (Iasky et al., 2003).

Palaeozoic traps in the Gascoyne Platform include Ordovician, Silurian, and Devonian reservoir rocks in rotated fault blocks, created by mid- to Late Permian and Late Jurassic rifting. Such traps may be effective if sealed by intraformational shales. Low dips and small fault displacements imply that such traps may be quite large. Other possible Palaeozoic plays in the southwestern offshore part of the platform include fault traps in which the Kockatea Shale seals the Tumblagooda Sandstone. These traps could have been charged by hydrocarbons that migrated updip from more deeply buried sections of the Kockatea Shale in the Abrolhos Sub-basin. The Wittecarra Sandstone (at the base of the Kockatea Shale) probably extends onto the southwestern part of the platform, where it is a possible objective in fault traps. In the northern part of the platform, east of Pendock 1, there are a few untested faulted anticlines along a north-northeasterly trending fault within the Gneudna Formation, in which reefal carbonate facies of the Point Maud Member of the Gneudna Formation may be sealed intraformationally (Iasky et al., 2003).

The most likely plays in the Merlinleigh Sub-basin are anticlines, fault dependent closures, and stratigraphic traps. A number of anticlines have been identified from seismic and outcrop data, but their extent at depth is unclear. The Quail structure is a large anticline plunging gently to the north in which Quail 1 was drilled downdip from the highest part of the structure. The southern limit of the structure is poorly defined, and additional control is needed to define an optimal location. Other smaller anticlines are present, such as the untested anticlinal structure lying about 40 km south-southeast of Quail 1 on the footwall of the Paddys Fault (Iasky et al., 1998a, fig. 46).

Fault plays are present throughout the Merlinleigh Sub-basin, and along the eastern margin they are proximal to Devonian source rocks that are presently in the oil-generation window. Farther west, such traps may be prospective for gas. In the Gneudna Formation, carbonate sections, if lenticular, could form stratigraphic traps charged from intraformational shales. The underlying Nannyarra Sandstone may also have potential in a fault trap; it is more likely to be of economic interest away from the eastern margin of the sub-basin, where the Devonian source rocks are within the oil-maturation window. Possible truncation traps may be present below the Lyons Group if basal shales seal the unconformably underlying Lower Carboniferous sandstone charged from Devonian or older source rocks.

Traps that formed during Late Carboniferous – Early Permian tectonism are more likely to be charged with oil from Devonian and Permian source rocks that underwent maximum oil expulsion during the Late Permian – Early Triassic. Traps formed during breakup and Miocene tectonism, however, may be charged from sources maturing in marginal areas if there were sufficient increases in heat flow.

Prospectivity

At the time of writing a total of 32 petroleum exploration and stratigraphic wells have been drilled on the Gascoyne Platform. Of these, 10 were drilled as new-field wildcats, which equates to one new-field wildcat per 12 000 km^2. Seven wells were drilled to test Birdrong Sandstone in Miocene anticlinal structures, and three (Yaringa 1, Carlston 1, and Edel 1) were drilled to test Palaeozoic structures, but were dry holes (Iasky et al., 2003). It is unclear from the available seismic data, which is mostly of very poor quality, if any of these wells tested a valid structure below the breakup unconformity. The only hydrocarbon shows in the Silurian and Devonian sections on the Gascoyne Platform to date include: traces of gas and residual oil from the Coburn Formation in Dirk Hartog 17B (Pudovskis, 1957); minor gas and oil shows from the Silurian and Devonian sections in Pendock 1 (Genoa Oil N.L., 1970); minor gas from the ?Tumblagooda Sandstone in Wandagee 1 (Pudovskis, 1962); and residual oil from the Dirk Hartog Group in Tamala 1 (Oceania Petroleum Pty Ltd, 1973). Of more than 40 wells, mostly drilled by WAPET in the Cape Range peninsula, only four had significant hydrocarbons within the Birdrong Sandstone: Rough Range 1 and 1A, with a 7.5-m oil column; Parrot Hill 1, which intersected a 6.2-m oil column; and Roberts Hill 1, which penetrated a thin oil zone. Even though Ellis and Jonasson (2002) indicated that the geochemical data are equivocal, Partington et al. (2003) implied that these oils are sourced from the Jurassic. Jurassic source rocks are considered amongst the most effective of the Northern Carnarvon Basin (Scott, 1992; Longley et al., 2002), but economic hydrocarbons from such a source are unlikely in the Gascoyne Platform as long-range migration is required. Furthermore, it is unlikely that Jurassic-sourced hydrocarbons have migrated south into the platform because few of the structures along the Rough Range Fault have yielded hydrocarbons. The only area in which such migration is feasible is along the Bernier Ridge (Lockwood and D'Ercole, in prep.), but even there it is unlikely that hydrocarbons could have migrated south of that basement high.

The maturity of the Silurian Coburn Formation and Devonian Gneudna Formation increases to the north, with the former presently mature for hydrocarbon generation, and the latter mostly in the early stage of maturation. The modelled peak expulsion of hydrocarbons from Silurian and Devonian source rocks during the Late Permian to

Middle Jurassic suggests that, to be effective, traps should have been emplaced before the Middle Jurassic. However, secondary migration into post-Late Jurassic structures may have taken place. For example, peak expulsion from the Triassic Kockatea Shale, which is within the oil-generative window along the southwestern margin of the Gascoyne Platform, was probably in the Late Jurassic. It is possible that hydrocarbons from the Kockatea Shale in the Perth Basin and Locker Shale in the Exmouth Sub-basin migrated into the Gascoyne Platform following Late Jurassic expulsion. Pre-Late Jurassic structures would be required to trap these hydrocarbons (Iasky et al., 2003).

Miocene anticlinal structures are the most prospective traps in the Gascoyne Platform. Even though most onshore tests of these structures did not produce significant hydrocarbons, offshore structures are probably more favourably located with respect to migration pathways from deeply buried Mesozoic source rocks. By comparison there are few valid tests of Palaeozoic objectives — only 3 wells had pre-breakup structural objectives: Edel 1 was drilled into a pre-breakup anticline formed over an igneous intrusion; Yaringa 1 was drilled to test a pre-Cretaceous anticlinal structure, but closure of the structure is uncertain; and in Carlston 1 either the objective thick limestone beds within the Gneudna Formation were absent or not reached.

The petroleum potential of the Woodleigh impact structure is limited by: the immaturity of the otherwise good to excellent source-rock characteristics of the Mesozoic section; the low maturity of the Silurian section in Woodleigh 2A and Yaringa 1; and the paucity of potential sealing sections.

The southern Merlinleigh Sub-basin is an area where there has been minimal petroleum exploration, with only two deep tests out of the 16 exploration wells drilled, and only regional coverage of seismic data. The sub-basin had a similar history to the northern Perth Basin in that deposition in both regions initiated from Late Carboniferous – Early Permian rifting and both were strongly affected by breakup. However, the lack of Mesozoic strata in the southern Merlinleigh Sub-basin limits its prospectivity. The primary objectives are the Devonian Gneudna Formation and Lower Permian Wooramel Group.

In the Merlinleigh Sub-basin, untested structural features have been identified from the existing regional seismic data (Crostella, 1995a; Iasky et al., 1998a), but require additional seismic data to be better defined. Because the western part of the southern Merlinleigh Sub-basin has undergone a greater degree of deformation than the rest of the sub-basin, a variety of structures, including anticlines and faults, are present. Areas updip of the major relay ramp between the Wandagee and Kennedy Range Faults should be considered as a target for exploration because of the greater degree of deformation in these areas compared to the rest of the sub-basin (Iasky et al., 1998a).

Summary

The first widespread deposition in the Southern Carnarvon Basin is demonstrated by redbed facies of the Tumblagooda Sandstone of probable Late Ordovician age (based on Early Silurian conodont faunas in overlying carbonate beds of the Dirk Hartog Group), although deposition may have commenced in the Late Cambrian based on a single conodont fauna of Early Ordovician age from Wandagee 1. Of the three higher breaks in the succession (earliest Devonian, mid-Devonian, and mid-Carboniferous), only the mid-Carboniferous break is associated with significant regional tectonism. At that time a major depocentre developed along the eastern margin of the basin (Merlinleigh, Byro, and Coolcalalaya Sub-basins), in which up to 5000 m of mid-Carboniferous to Upper Permian strata accumulated. Low thermal maturities of the Silurian section across the Gascoyne Platform to the west imply that there was little, if any, Carboniferous–Permian deposition on the platform.

Three regional tectonic events probably affected the basin during the subsequent gap in the succession (latest Permian to earliest Cretaceous): Late Permian rifting, best seen in the northern Perth Basin; and Late Jurassic rifting and Early Cretaceous breakup, both associated with the separation of Australia from Greater India. Deformation associated with these events appears to have folded, tilted, and faulted the Palaeozoic strata within the Merlinleigh, Byro, and Coolcalalaya Sub-basins noticeably more than strata in the Gascoyne Platform. The succeeding Cretaceous–Cainozoic succession is mostly flat lying, but does show Miocene inversion of some faults associated with the development of mostly north–south oriented anticlines. The only other deformation clearly evident is associated with the Late Devonian Woodleigh impact structure, which is probably 120 km in diameter, east of Shark Bay.

Geochemical analyses indicate that the best source beds are within the Upper Silurian Coburn Formation in Yaringa East 1 (deepening) on the southern Gascoyne Platform (Ghori, 2002), and the Upper Devonian Gneudna Formation in Barrabiddy 1A on the northern Gascoyne Platform (Ghori, 1998b). The Silurian source beds have organic richness of over 7% TOC, potential yield (S_1 + S_2) of up to 38 mg/g, and hydrogen index of up to 505, whereas Devonian source beds have organic richness of up to 13.5% TOC, potential yield of up to 40 mg/g, and hydrogen index of up to 267. Although these beds are organic-rich, oil-prone, and laminated within carbonate facies, they are thin and probably of limited extent and volume. By comparison, Permian source beds within the Lower Permian Wooramel and Byro Groups appear to be thick and widespread within the Carboniferous–Permian depocentres to the east (Merlinleigh, Byro, and Coolcalalaya Sub-basins). In the Merlinleigh Sub-basin, the organic richness of these beds is up to 16% TOC, with an average of 7%, and potential yield is up to 12 mg/g, with an average yield of 6 mg/g, and are predominantly gas generating.

Analyses of hydrocarbon shows in the Southern Carnarvon Basin are insufficient to differentiate into discrete families or to correlate with likely source rocks. Therefore, possible petroleum systems, as defined by Magoon and Dow (1994), cannot be confidently delineated. However, the regional stratigraphic distribution of likely source, reservoir, and sealing rocks limits the number of possible petroleum systems to those that may be charged by the Silurian Dirk Hartog Group, Devonian Gneudna Formation, and the Lower Permian Wooramel and (possibly) Byro Groups (Fig. 7).

Geohistory modelling indicates that petroleum generation and migration from Silurian and Devonian source beds peaked during the Permian, whereas generation and migration from Permian source beds peaked during the Triassic. Therefore, mid-Carboniferous – Early Permian structures are the most prospective, even though they may have been breached by later tectonism. Remigration into younger structures of breakup or Miocene age, or both, is also possible, but less likely.

Possible traps within the southern Gascoyne Platform incorporate sealing rocks of the Dirk Hartog Group and reservoirs in the underlying Tumblagooda Sandstone or, in the northern Gascoyne Platform and Merlinleigh Sub-basin, intraformational seal and reservoir in the Gneudna Formation, with an additional reservoir provided by the underlying Nannyarra Sandstone. Offshore the Lower Triassic Kockatea Shale may seal the Tumblagooda Sandstone south of Shark Bay. In the Merlinleigh Sub-basin, the Lower Permian Wooramel and Byro Groups contain organic-rich shales and sandstones with excellent reservoir characteristics, such as the Moogooloo Sandstone (Havord, 1998), and potential sealing units such as the Billidee Formation (Lavering, 1982; Percival and Cooney, 1985; Crostella, 1995a). Other seal–reservoir combinations are geographically more restricted, and therefore less likely to be effective.

Significant tectonic events in the mid-Carboniferous – Early Permian, Early Cretaceous, and Miocene are evident from seismic and outcrop data in the Merlinleigh Sub-basin (Iasky and Mory, 1999). On the Gascoyne Platform, by comparison, seismic data show that structuring is less intense, at least away from the Permian sub-basins to the east (Iasky et al., 2003). Vitrinite reflectance and AFTA data from the Gascoyne Sub-basin indicate that thermal cooling episodes occurred during the Permian, Late Jurassic, and Cainozoic (Gibson et al., 1998, 2000); on regional grounds, these events also probably affected adjacent sub-basins. Of the tectonic events, mid-Carboniferous – Lower Permian rifting appears to be the most likely to form viable traps. Structures of this age immediately preceded possible hydrocarbon generation and migration from Silurian–Devonian and Lower Permian source rocks during the Early Permian and Permian–Triassic, respectively, as indicated by geohistory modelling. The complex and varied depositional and erosional history of the basin, however, implies preservation is a major exploration risk. In addition, imaging of likely traps in the Southern Carnarvon Basin remains problematic with the existing seismic data, especially in the onshore part of the Gascoyne Platform where the seismic data are too sparse to map horizons, and data quality below the Cretaceous is usually extremely poor.

References

BAKER, J. C., HAVORD, P. J., MARTIN, K. J., and GHORI, K. A. R., 2000, Diagenesis and petrophysics of the Early Permian Moogooloo Sandstone, Southern Carnarvon Basin, Western Australia: American Association of Petroleum Geologists, Bulletin, v. 84, p. 260–265.

BRADSHAW, B. E., ROLLET, N., TOTTERDELL, J. M., and BORISSOVA, I., 2003, A revised structural framework for frontier petroleum basins on the southern and southwestern Australian continental margin: Geoscience Australia, Record 2003/3.

BUNT, R. J. W., POWELL, W. D., and SCHOLEFIELD, T., 2001, The Tubridgi gas field rejuvenated: APPEA Journal, v. 41(1), p. 429–447.

CLAPP, F. G., 1926, Oil prospects of the North West Basin of Western Australia: American Association of Petroleum Geologists, Bulletin, v. 10(11), p. 1136–1149.

CLARKE, E. de C., and TEICHERT, C., 1948, Cretaceous stratigraphy of the Lower Murchison River area, Western Australia: Royal Society of Western Australia, Journal, v. 32, p. 19–48.

CONDIT, D. D., 1935, Oil possibilities in the North West district, Western Australia: Economic Geology, v. 30, p. 860–878.

CONDON, M. A., 1954, Progress report on the stratigraphy and structure of the Carnarvon Basin, Western Australia: Australia BMR, Report 15, 163p.

CONDON, M. A., 1965, The Geology of the Carnarvon Basin, Western Australia, Part 1: Pre-Permian stratigraphy: Australia BMR, Bulletin 77, 82p.

CONDON, M. A., 1967, The Geology of the Carnarvon Basin, Western Australia, Part 2: Permian stratigraphy: Australia BMR, Bulletin 77, 191p.

CONDON, M. A., 1968, The Geology of the Carnarvon Basin, Western Australia, Part 3: Post-Permian stratigraphy; structure; economic geology: Australia BMR, Bulletin 77, 68p.

CONDON, M. A., JOHNSTONE, D., PRITCHARD, C. E., and JOHNSTONE, M. H., 1956, The Giralia and Marrilla Anticlines, North-west Division, Western Australia: Australia BMR, Bulletin 25, 86p.

CROSTELLA, A., 1995a, The structural evolution and the hydrocarbon potential of the Merlinleigh and Byro Sub-basins, Carnarvon Basin, Western Australia: Western Australia Geological Survey, Report 45, 36p.

CROSTELLA, A., 1995b, An evaluation of the hydrocarbon potential of the onshore northern Perth Basin, Western Australia: Western Australia Geological Survey, Report 43, 67p.

CROSTELLA, A., 1996, North West Cape petroleum exploration analysis of results to early 1995: Western Australia Geological Survey, Record 1996/3, 45p.

CROSTELLA, A., 1997, Hydrocarbon potential of the North West Cape area, Carnarvon Basin, Western Australia: Petroleum Exploration Society of Australia, Journal, v. 24, p. 15–24

CROSTELLA, A., 2001, Geology and petroleum potential of the Abrolhos Sub-basin, Western Australia: Western Australia Geological Survey, Report 75, 57p.

CROSTELLA, A., and IASKY, R. P., 1997, Structural interpretation and hydrocarbon potential of the Giralia area, Carnarvon Basin: Western Australia Geological Survey, Report 52, 38p.

CROSTELLA, A., IASKY, R. P., BLUNDELL, K. A., YASIN, A. R., and GHORI, K. A. R., 2000, Petroleum geology of the Peedamullah Shelf and Onslow Terrace, Northern Carnarvon Basin, Western Australia: Western Australia Geological Survey, Report 73, 119p.

DENTITH, M. C., BRUNER, I., LONG, A., MIDDLETON, M. F., and SCOTT, J., 1993, Structure of the eastern margin of the Perth Basin, Western Australia: Exploration Geophysics, v. 24, p. 455–462.

DIXON, M., HAIG, D. W., MORY, A. J., BACKHOUSE, J., GHORI, K. A. R., HOWE, R., and MORRIS, P. A., 2003a, GSWA Edaggee 1 well completion report (interpretive), Gascoyne Platform, Southern Carnarvon Basin, Western Australia: Western Australia Geological Survey, Record 2003/8, 80p.

DIXON, M., HAIG, D. W., MORY, A. J., BACKHOUSE, J., GHORI, K. A. R., and MORRIS, P. A., 2003b, GSWA Yinni 1 well completion report (interpretive), Gascoyne Platform, Southern Carnarvon Basin, Western Australia: Western Australia Geological Survey, Record 2003/7, 44p.

ELLIS, G. K., and JONASSON, K. E., 2002, Rough Range Oil Field, Carnarvon Basin, *in* The sedimentary basins of Western Australia 3 *edited by* M. KEEP and S. J. MOSS: Petroleum Exploration Society of Australia, Western Australian Basins Symposium, Perth, W.A., 2002, Proceedings, p. 707–717.

ELLIS, G. K., PITCHFORD, A., and BRUCE, R. H., 1999, Barrow Island oil field: The APPEA Journal, v. 39 (1), p. 158–176.

EL-TABAKH, M., MORY, A. J., and SCHREIBER, B. C., in press, Anhydrite cements after dolomitization of shallow marine Silurian carbonates, Gascoyne Platform, Southern Carnarvon Basin, Western Australia: Sedimentary Geology

EMMETT, J. K., 1981, Geochemical report, Merlinleigh Sub-basin, Western Australia, Esso Australia Ltd: Western Australia Geological Survey, Statutory petroleum exploration report, S6188 (unpublished).

EVERINGHAM, I. B., 1968, Seismicity of Western Australia: Australia BMR, Report 132, 44p.

EYLES, N., 1993, Earth's glacial record and its tectonic setting: Earth Science Reviews, v. 35, p. 1–248.

EYLES, N., MORY, A. J., and BACKHOUSE, J., 2002, Carboniferous-Permian palynostratigraphy of west Australian marine rift basins: resolving tectonic and eustatic controls during Gondwanan glaciations: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 184 (3–4), p. 305–319.

EYLES, C. H., MORY, A. J., and EYLES, N., 2003, Carboniferous–Permian facies and tectono-stratigraphic successions of the glacially influenced and rifted Carnarvon Basin, Western Australia: Sedimentary Geology, v. 155, p. 63–86.

GEARY, J. K., 1970, Offshore exploration of the southern Carnarvon Basin: APEA Journal, v. 10(2), p. 9–15.

GENOA OIL N.L., 1970, Final report on Pendock ID No. 1 well, Western Australia: Western Australia Geological Survey, Statutory petroleum exploration report, S49 A3 (unpublished).

GHORI, K. A. R., 1996, Petroleum source rocks, Merlinleigh and Byro Sub-basins, Carnarvon Basin, Western Australia: Western Australia Geological Survey, Record 1995/5, 102p.

GHORI, K. A. R., 1998a, Petroleum generating potential and thermal history of the Palaeozoic, Carnarvon Basin, Western Australia, *in* The sedimentary basins of Western Australia 2, *edited by* P. G. PURCELL and R. R. PURCELL: Petroleum Exploration Society of Australia, Western Australian Basins Symposium, Perth, W.A., 1998, Proceedings, p. 553–567.

GHORI, K. A. R., 1998b, Geochemistry of the Devonian, Barrabiddy 1A, Gascoyne Platform, Carnarvon Basin, Western Australia: Petroleum Exploration Society of Australia, Journal, v. 26, p. 136–146.

GHORI, K. A. R., 1999, Silurian–Devonian petroleum source-rock potential and thermal history, Carnarvon Basin, Western Australia: Western Australia Geological Survey, Report 72, 88p.

GHORI, K. A. R., 2002, High-quality oil-prone source rocks within carbonates of the Silurian Dirk Hartog Group, Gascoyne Platform, Western Australia: Western Australia Geological Survey, Annual Review 2000–01, p. 58–62.

GHORI, K. A. R., IASKY, R. P., and MORY, A. J., in prep., Modelling petroleum generation within the Palaeozoic succession of the Carnarvon Basin, Western Australia.

GIBSON, H. J., MARSHALLSEA, S. J., and WATSON, P. G. F., 1998, Thermal history reconstruction in Carnarvon Basin wells Barrabiddy 1A, Yaringa East 1, Coburn 1 and an outcrop sample using apatite fission track analysis and vitrinite reflectance; Geotrack Report 670: Western Australia Geological Survey, Statutory petroleum exploration report, S31321 A1 (unpublished).

GIBSON, H. J., O'BRIEN, C., and WATSON, P. G., 2000, Thermal history reconstruction in Carnarvon Basin wells Candace 1, Pendock 1, Wandagee 1, Woodleigh 2A and Echo Bluff 1 using apatite fission track analysis and vitrinite reflectance; Geotrack Report 764: Western Australia Geological Survey, Statutory petroleum exploration report, S31450 A1 (unpublished).

GORTER, J. D., MORY, A. J., and NICOLL, R. S., 1998, Sequence stratigraphy and hydrocarbon potential of the Middle to Upper Devonian sequences in the Southern Carnarvon Basin, Western Australia, *in* The sedimentary basins of Western Australia 2, *edited by* P. G. PURCELL and R. R. PURCELL: Petroleum Exploration Society of Australia, Western Australian Basins Symposium, Perth, W.A., 1998, Proceedings, p. 373–396.

GORTER, J. D., NICOLL, R. S., and FOSTER, C. N., 1994, Lower Palaeozoic facies in the Carnarvon Basin, Western Australia: Stratigraphy and hydrocarbon prospectivity, *in* The Sedimentary Basins of Western Australia *edited by* P. G. PURCELL and R. R. PURCELL: Petroleum Exploration Society of Australia, Western Australian Basins Symposium, Perth, W.A., 1994, Proceedings, p. 373–396.

HAIG, D. W., in press, Palaeobathymetric zonation of foraminifera from Lower Permian shale deposits of a high-latitude southern interior sea: Marine Micropalaeontology.

HAIG, D. W., and MORY, A. J., in prep., New record of marine Eocene from Kalbarri, Western Australia: Royal Society of Western Australia, Journal

HARRIS, L. B., 1994, Structural and tectonic synthesis for the Perth Basin, Western Australia: Journal of Petroleum Geology, v. 17(2), p. 129–156.

HAVORD, P., 1998, Assessment and prediction of petroleum reservoir quality in the Moogooloo Sandstone and Keogh Formation, Southern Carnarvon Basin, Western Australia: Western Australia Geological Survey, Record 1998/4, 68p.

HOBSON, R. A., 1936, Summary of petroleum exploration in Western Australia to January 1935: Western Australia Mines Department, Annual Report for 1935, p. 62–74.

HOCKING, R. M., 1991, The Silurian Tumblagooda Sandstone, Western Australia: Western Australia Geological Survey, Report 27, 124p.

HOCKING, R. M., 1994, Subdivisions of Western Australian Neoproterozoic and Phanerozoic sedimentary basins: Western Australia Geological Survey, Record 1994/4, 84p.

HOCKING, R. M., 2000, Geology of the Southern Carnarvon Basin — a field guide: Western Australia Geological Survey, Record 2000/10, 102p.

HOCKING, R. M., MOORS, H. T., and van de GRAAFF, W. J. E., 1987, Geology of the Carnarvon Basin, Western Australia: Western Australia Geological Survey, Bulletin 133, 289p.

HOCKING, R. M., MORY, A. J., and WILLIAMS, I. R., 1994, An atlas of Neoproterozoic and Phanerozoic basins of Western Australia, *in* The sedimentary basins of Western Australia *edited by* P. G. PURCELL and R. R. PURCELL: Petroleum Exploration Society of Australia, Western Australian Basins Symposium, Perth, W.A., 1994, Proceedings, p. 21–43.

HOCKING, R. M., WILLIAMS, S. J., LAVARING, I. H., and MOORE, P. S., 1985, Winning Pool – Minilya, W.A. (2nd edition): Western Australia Geological Survey, 1:250 000 Geological Series Explanatory Notes, 36p.

HOUGH, R. M., LEE, M. R., and BEVAN, A. W. R., 2001, Shocked quartz and more: Woodleigh impact structure, Western Australia: Meteoritics and Planetary Science, v. 36 (suppl.), p. A84–A85.

IASKY, R. P., D'ERCOLE, C., GHORI, K. A. R., MORY, A. J., and LOCKWOOD, A. M., 2003, Structure and petroleum prospectivity of the Gascoyne Platform, Western Australia: Western Australia Geological Survey, Report 87, 56p.

IASKY, R. P., and MORY, A. J., 1999, Geology and petroleum potential of the Gascoyne Platform, Southern Carnarvon Basin, Western Australia: Western Australia Geological Survey, Report 69, 46p.

IASKY, R. P., MORY, A. J., and BLUNDELL, K. B., 2001, The geophysical interpretation of the Woodleigh impact structure, Southern Carnarvon Basin, Western Australia: Western Australia Geological Survey, Report 79, 41p.

IASKY, R. P., MORY, A. J., GHORI, K. A. R., and SHEVCHENKO, S. I., 1998a, Structure and petroleum potential of the southern Merlinleigh Sub-basin, Carnarvon Basin, Western Australia: Western Australia Geological Survey, Report 61, 63p.

IASKY, R. P., MORY, A. J., and SHEVCHENKO, S., 1998b, A structural interpretation of the Gascoyne Platform, Southern Carnarvon Basin, WA, *in* The sedimentary basins of Western Australia *edited by* P. G. PURCELL and R. R. PURCELL: Petroleum Exploration Society of Australia, Western Australian Basins Symposium, Perth, W.A., 1998, Proceedings, p. 589–598.

JAQUES, A. L., LEWIS, J. D., and SMITH, C. B., 1986, The kimberlites and lamproites of Western Australia: Western Australia Geological Survey, Bulletin 132, 268p.

JONES, P. J., NICOLL, R. S., EDWARDS, D. S., KENNARD, J. M., and GLENN, K. C., 1998, Canning Basin: Australian Geological Survey Organisation, Biozonation and Stratigraphy Chart 2.

JONES, P. J., NICOLL, R. S., SHERGOLD, J. H., FOSTER, C. B., KENNARD, J. M., and COLWELL, J. B., 1997, Petrel Sub-basin: Australian Geological Survey Organisation, Biozonation and Stratigraphy Chart 1.

KOEBERL, C., HOUGH, R. M., BOAMAH, D., FRENCH, B. M., McDONALD, I., and REIMOLD, W. U., 2001, Woodleigh impact structure, Australia: shock petrography and geochemical studies: Meteoritics and Planetary Science, v. 36 (suppl.), p. A101.

KONECKI, M. C., DICKENS, J. M., and QUINLAN, T., 1958, The geology of the coastal area between the lower Gascoyne and Murchison rivers, Western Australia: Australia BMR, Report 37, 144p.

LAVERING, I. H., 1982, Field study of the Devonian and Carboniferous carbonates and clastics of the Merlinleigh Sub-basin: Western Australia Geological Survey, Statutory petroleum exploration report, S3817 A1 (unpublished).

LE BLANC SMITH, G., and MORY, A. J., 1995, Geology and Permian coal resources of the Irwin Terrace, Western Australia: Western Australia Geological Survey, Report 44, 60p.

LEHMANN, P. R., 1967, Kennedy Range 1 well completion report: Western Australia Geological Survey, Statutory petroleum exploration report, S322 A1 (unpublished).

LE MAITRE, R. W., 1972, Volcanic rocks from Edel No. 1 petroleum exploration well, offshore Carnarvon Basin, Western Australia: Australian Geological Society, Journal, v. 22, p. 167–174.

LEVER, H., 2002, Stratigraphy of the Upper Permian Kennedy Group of the onshore Carnarvon Basin (Merlinleigh Sub-basin), Western Australia: Australian Journal of Earth Sciences, v. 49, p. 539–550.

LOCKWOOD, A. M., and D'ERCOLE, C. in prep., A geophysical interpretation of the Bernier Sub-basin and the northwestern Gascoyne Platform, Southern Carnarvon Basin: Western Australia Geological Survey, Report.

LONGLEY, I. M., BUESSENSCHUETT, C., CLYDSDALE, L., CUBITT, C. J., DAVIS, R. C., JOHNSON, M. K., MARSHALL, N. M., MURRAY, A. P., SOMERVILLE, R., SPRY, T. B., and THOMPSON, N. B., 2002, The North West Shelf of Australia — a Woodside perspective, *in* The sedimentary basins of Western Australia 3 *edited by* M. KEEP and S. J. MOSS: Petroleum Exploration Society of Australia, Western Australian Basins Symposium, Perth, W.A., 2002, Proceedings, p. 27–86.

LOWELL, J. D., 1985, Structural styles in petroleum exploration: Tulsa, Oklahoma, Oil and Gas Consultants International Inc. (OGCI), 477p.

MAGOON, L. B., and DOW, W. (editors), 1994, The petroleum system — from source to trap: American Association of Petroleum Geologists, Memoir 60, 655p.

MAITLAND, A. G., 1909, Geological investigations in the country lying between 21°30' and 25°30'S lat. and 113°30' and 118°30'E long., embracing parts of the Gascoyne, Ashburton, and West Pilbara Goldfields: Western Australia Geological Survey, Bulletin 33, 184p.

MALCOLM, R. J., POTT, M. C., and DELPHOS, E., 1991, A new tectono-stratigraphic synthesis of the North West Cape area: APEA Journal, v. 31(1), p. 154-176.

MOORE, P. S., and HOCKING, R. M., 1983, Significance of hummocky cross-stratification in the Permian of the Carnarvon Basin, Western Australia: Journal of the Geological Society of Australia, v. 30, p. 323–331.

MOORE, P. S., HOCKING, R. M., and DENMAN, P. D., 1980, Sedimentology of the Kennedy Group (Permian), Carnarvon Basin, Western Australia: Western Australia Geological Survey, Annual Report 1979, p. 65–72.

MORY, A. J., (compiler), 1996a, GSWA Ballythanna 1 well completion report, Byro Sub-basin, Carnarvon Basin: Western Australia Geological Survey, Record 1996/6, 48p.

MORY, A. J., (compiler), 1996b, GSWA Gneudna 1 well completion report, Merlinleigh Sub-basin, Carnarvon Basin, Western Australia: Western Australian Geological Survey, Record 1996/6, 51p.

MORY, A. J., and BACKHOUSE, J., 1997, Permian stratigraphy and palynology of the Southern Carnarvon Basin, Western Australia: Western Australia Geological Survey, Report 51, 41p.

MORY, A. J., and DIXON, M., 2002a, GSWA Yinni 1 well completion report (basic data), Gascoyne Platform, Southern Carnarvon Basin, Western Australia: Western Australia Geological Survey, Record 2002/6, 13p.

MORY, A. J., and DIXON, M., 2002b, GSWA Boologooro 1 well completion report (basic data), Gascoyne Platform, Southern Carnarvon Basin, Western Australia: Western Australia Geological Survey, Record 2002/7, 17p.

MORY, A. J., and DIXON, M., 2002c, GSWA Edaggee 1 well completion report (basic data), Gascoyne Platform, Southern Carnarvon Basin, Western Australia: Western Australia Geological Survey, Record 2002/8, 16p.

MORY, A. J., and DUNN, P., 1990, Geological evolution and mineral potential of the Bonaparte, Canning, Ord and Officer Basins, *in* Geology of the mineral deposits of Australia and Papua New Guinea *edited by* F. E. HUGHES: Australian Institute of Mining and Metallurgy, Monograph 14, p. 1089–1096.

MORY, A. J., and IASKY, R. P., 1996, Stratigraphy and structure of the onshore northern Perth Basin, Western Australia: Western Australia Geological Survey, Report 46, 102p.

MORY, A. J., IASKY, R. P., GLIKSON, A. Y., and PIRAJNO, F., 2000, Woodleigh, Carnarvon Basin, Western Australia: a new 120 km-diameter impact structure: Earth and Planetary Science Letters, v. 177(1–2), p. 119–128.

MORY, A. J., IASKY, R. P., GLIKSON, A. Y., and PIRAJNO, P., 2001, Response to 'Critical comment on A. J. Mory et al., 2000, Woodleigh, Carnarvon Basin, Western Australia: a new 120 km diameter impact structure' by W. U. Reimold and C. Koeberl: Earth and Planetary Science Letters, v. 184 (1), p. 359–365.

MORY, A. J., IASKY, R. P., and SHEVCHENKO, S., 1998a, The Coolcalalaya Sub-basin: a forgotten frontier between the Perth and Carnarvon basins, WA, *in* The sedimentary basins of Western Australia *edited by* P. G. PURCELL and R. R. PURCELL: Petroleum Exploration Society of Australia, Western Australian Basins Symposium, Perth, W.A., 1998, Proceedings, p. 613–622.

MORY, A. J., NICOLL, R. S., and GORTER, J. D., 1998b, Lower Palaeozoic correlations and thermal maturity, Carnarvon Basin, W.A., *in* The sedimentary basins of Western Australia 2 *edited by* P. G. PURCELL and R. R. PURCELL: Petroleum Exploration Society of Australia; Western Australian Basins Symposium, Perth, W.A., 1998, Proceedings, p. 599–611.

MORY, A. J., PIRAJNO, F., GLIKSON, A. Y., and COKER, J. (compilers), 2001, GSWA Woodleigh 1, 2, and 2A well completion report, Woodleigh impact structure, Southern Carnarvon Basin, Western Australia: Western Australia Geological Survey, Record 2001/6, 147p.

MORY, A. J., and YASIN, A. R., (compilers), 1999, GSWA Barrabiddy 1 and 1A well completion report, Wandagee Ridge, Southern Carnarvon Basin, Western Australia: Western Australia Geological Survey, Record 1999/3, 84p.

MORY, A. J., and YASIN, A. R., 1998, GSWA Mooka 1 well completion report, Gascoyne Platform, Southern Carnarvon Basin, Western Australia: Western Australia Geological Survey, Record 1998/6, 49p.

NICOLL, R. S., and GORTER, J. D., 1995, Devonian–Carboniferous stratigraphy of Quail 1, Carnarvon Basin, Western Australia: regional implications for geohistory and hydrocarbon prospectivity: AGSO Journal of Australian Geology and Geophysics, v. 15(4), p. 413–420.

NICOLL, R. S., MORY, A. J., BACKHOUSE, J., SHAFIK, S., and GLENN, K. C., 1998, Southern Carnarvon Basin: Australian Geological Survey Organisation, Biozonation and Stratigraphy Chart 4.

OCEANIA PETROLEUM PTY LTD, 1973, Tamala No 1 well, Western Australia, well completion report: Western Australia Geological Survey, Statutory petroleum exploration report, S833 A1 V1 (unpublished).

OCEAN VENTURES PTY LTD, 1972, Edel 1 well completion report: Western Australia Geological Survey, Statutory petroleum exploration report, S727 V1 (unpublished).

PARTINGTON, M., AURISCH, K., CLARK, W., NEWLANDS, I., PHELPS, S., SENYCIA, P., SIFFLEET, P., and WALKER, T., 2003, The hydrocarbon potential of exploration permits WA-299-P and WA-300-P, Carnarvon Basin: a case study: APPEA Journal, v. 43(1), p. 339–361.

PERCIVAL, I. G., and COONEY, P. M., 1985, Petroleum geology of the Merlinleigh Sub-basin: APEA Journal, v. 25, p. 190–203.

PERRY, W. J., and DICKINS, J. M., 1960, The geology of the Badgeradda area, Western Australia: Australia BMR, Report 46, 38p.

PLAYFORD, P. E., and CHASE, R. E., 1955, Carnarvon Basin water bores; West Australian Petroleum Pty Ltd: Western Australia Geological Survey, Statutory petroleum exploration report, S126 A1 (unpublished).

POWELL, C. M., and VEEVERS, J. J., 1987, Namurian uplift in Australia and South America triggered the main Gondwanan glaciation: Nature, v. 326, p. 177-179.

PUDOVSKIS, V., 1957, Geological well summary Dirk Hartog No. 17B (deep test); West Australian Petroleum Exploration Pty Ltd: Western Australia Geological Survey, Statutory petroleum exploration report, S557 A1 V17 (unpublished).

PUDOVSKIS, V., 1962, Wandagee no. 1 well completion report; West Australian Petroleum Exploration Pty Ltd: Western Australia Geological Survey, Statutory petroleum exploration report, S19 A1 (unpublished).

RAGGATT, H. G., 1936, Geology of the North-West Basin, Western Australia, with particular reference to the stratigraphy of the Permo-Carboniferous: Royal Society of New South Wales, Journal, v. 70, p. 100–174.

REIMOLD, W. U., and KEOBERL, C., 2000, Critical comment on: A. J. Mory et al. ‘Woodleigh, Carnarvon Basin, Western Australia: a new 120 km diameter impact structure’: Earth and Planetary Science Letters, v. 184, p. 353–357.

RENNE, P. R., REIMOLD, W. U., KOEBERL, C., HOUGH, R. M., and CLAEYS, P., 2002, Comment on: ‘K–Ar evidence from illitic clays of a Late Devonian age for the 120 km diameter Woodleigh impact structure, Southern Carnarvon Basin, Western Australia’, by I. T. Uysal, S. D. Golding, A. Y. Glikson, A. J. Mory and M. Glikson: Earth and Planetary Science Letters, v. 201, p. 247–252.

SCOTT, J., 1992, Accurate recognition of source rock character in the Jurassic of the North West Shelf, Western Australia: APEA Journal, v. 32(1), p. 289–299.

SHAFIK, S., 1990, Late cretaceous nannofossil biostratigraphy and biogeography of the Australian western margin: Australia BMR, Geology and Geophysics, Report 295, 164p.

SUMMONS, R. E., BOREHAM, C. J., FOSTER, C. B., MURRAY, A. P., and GORTER, J. D., 1995, Chemostratigraphy and composition of oils in the Perth Basin, Western Australia: APEA Journal, v. 35(1), p. 613–632.

SYMONDS, P. A., and CAMERON, P. J., 1977, The structure and stratigraphy of the Carnarvon Terrace and Wallaby Plateau: APEA Journal, v. 17(1), p. 30–41.

TEARPOCK, D. J., and BISCKE, R. E., 1991, Applied subsurface geological mapping: Englewood Cliffs, New Jersey, Prentice Hall, 648p.

TEICHERT, C., 1940, Marine Jurassic in the North-West Basin, Western Australia: Journal of the Royal Society of Western Australia, v. 26, p. 17–25.

THERRIAULT, A. M., GRIEVE, R. A. F., and REIMOLD, W. U., 1997, Original size of the Vredefort Structure: implication for the geological evolution of the Witwatersrand Basin: Meteoritic and Planetary Science, v. 32, p. 71–77.

TREWIN, N. H., 1993a, Mixed aeolian sandsheet and fluvial deposits in the Tumblagooda Sandstone (Late Silurian) of Western Australia: Geological Society of London, Special Publication, v. 73, p. 219–230.

TREWIN, N. H., 1993b, Controls on fluvial deposition in mixed fluvial and aeolian facies within the Tumblagooda Sandstone (?late Silurian) of Kalbarri, Western Australia: Sedimentary Geology, v. 85, p. 387–00.

TREWIN, N. H., and McNAMARA, K. J., 1995, Arthropods invade the land: trace fossils and palaeoenvironments of the Tumblagooda Sandstone (?late Silurian) of Kalbarri, Western Australia: Transactions of the Royal Society of Edinburgh, Earth Sciences, v. 85, p. 177–210.

UYSAL, I. T., GOLDING, S. D., GLIKSON, A. Y., MORY, A. J., and GLIKSON, M., 2001, K–Ar evidence from illitic clays of a Late Devonian age for the 120 km diameter Woodleigh impact structure, Southern Carnarvon Basin, Western Australia: Earth and Planetary Science Letters, v. 192, p. 281–289.

UYSAL, I. T., GOLDING, S. D., GLIKSON, A. Y., MORY, A. J., GLIKSON, M., IASKY, R. P., and PIRAJNO, F., 2002, Reply to “Comment on ‘K–Ar evidence from illitic clays of a Late Devonian age for the 120 km diameter Woodleigh impact structure Southern Carnarvon Basin, Western Australia’”: Earth and Planetary Science Letters, v. 201, p. 253–260.

van de GRAAFF, W. J. E., CROWE, R. W. A., BUNTING, J. A., and JACKSON, M. J., 1977, Relict Early Cainozoic drainages in arid Western Australia: Zeitschrift für Geomorphologie NF, v. 21, p. 379–400.

VEEVERS, J. J., 1991, Mid-Cretaceous tectonic climax, Late Cretaceous recovery, and Cainozoic relaxation in the Australian region, *in* The Cainozoic in Australia: a re-appraisal of the evidence *by* M. A. S. WILLIAMS, A. P. DECKKER, and A. P. KERSHAW: Geological Society of Australia, Special Publication, no. 18, p. 1–14.

WARRIS, B. J., 1994, The hydrocarbon potential of the onshore Carnarvon Basin, *in* The sedimentary basins of Western Australia *edited by* P. G. and R. R. PURCELL: Petroleum Exploration Society of Australia, Western Australian Basins Symposium, Perth, W.A., 1994, Proceedings, p. 365–372.

WESTPHAL, H., and AIGNER, T., 1997, Seismic stratigraphy and subsidence analysis in the Barrow-Dampier Sub-basin, Northwest Australia: American Association of Petroleum Geologists, Bulletin, v. 81(10), p. 1721–1749.

WHITEHEAD, J., GRIEVE, R. A. F., and SPRAY, J., 2003, Planar deformation features in the Woodleigh impact structure, Western Australia, and their bearing on the degree of structural uplift in the structure: Geological Society of America, 38th Annual Meeting, Halifax, Nova Scotia, 2003, Paper no. 7-18.

WITHJACK, M. O., ISLAM, Q. T., and LaPOINTE, P. R., 1995, Normal faults and their hanging-wall deformation — an experimental study: American Association of Petroleum Geology, Bulletin, v. 79, p. 1–18.

YASIN, A. R., and MORY, A. J., (compilers), 1999a, Coburn 1 well completion report, Gascoyne Platform, Southern Carnarvon Basin, Western Australia: Western Australia Geological Survey, Record 1999/5, 99p.

YASIN, A. R., and MORY, A. J., (compilers), 1999b, Yaringa East 1 well completion report, Gascoyne Platform, Southern Carnarvon Basin, Western Australia: Western Australia Geological Survey, Record 1999/7, 53p.

Appendix 1

Revised well index sheet for Mooka 1

ORGANIZATION: Geological Survey of Western Australia
WELL: GSWA Mooka 1
SPUDDED: 18 October 1996
COMPLETED: 26 October 1996
TD: 418 m
STATUS: Abandoned

BASIN: Carnarvon Basin
SUB-BASIN: Gascoyne Platform
ELEVATION (GL): 120 m AHD (approx.)
LATITUDE: 24°58'30"S; **LONGITUDE:** 114°48'25"E
NORTHING: 7235990; **EASTING:** 278620 (MGA Zone 50)

Statutory Petroleum Exploration Report No.: S20372
TYPE: Stratigraphic

FORMATION	TOPS (m)		LITHOLOGIC SUMMARY
	DRILL	SUBSEA	
Alluvium	surface	+120	light-brown, fine- to coarse-grained sand; granules, pebbles
Gearle Siltstone	23.5	+96.5	dark-grey to black siltstone, pyritic, soft
Windalia Radiolarite	47	+73	dark-grey siltstone, hard; bedded chert
Muderong Shale	77	+51	medium- to dark-grey shale
Birdrong Sandstone	80.5	+39.5	medium-grey, fine- to coarse-grained sandstone; minor glauconite
Nannyarra Sandstone	93	+27	light-grey, brown, medium- to coarse-grained sandstone; minor green to brown shale, chloritic, micaceous
Sweeney Mia Formation	200.6	-80.6	brown mudstone; light-grey to white, gypsiferous limestone; breccia; gypsum veins; thinly bedded sandstone
?Kopke Sandstone	260.5	-140.5	light-grey, fine- to very coarse grained pebbly sandstone, minor mudstone and dolostone at base
Coburn Formation	281	-161	light-grey dolostone, skeletal debris, ooids, gypsiferous, gypsum veins

CORES

Continuously cored; HQ: 80.3 – 145.3 m (80.2% recovery)
NQ: 145.3 – 418 m (99.6% recovery)

LOGS

Run 1:	
GR, Limestone-Neutron porosity	418–0 m
Sonic, Comp. Density, Resistivity (shallow and deep)	418–120 m
Caliper	418–120 m
Run 2:	
GR, Limestone-Neutron porosity	160–0 m
Sonic, Comp. Density, Resistivity (shallow and deep)	160–120 m
Caliper	160–120 m

CASING

HW	(OD 114.3 mm, ID 101.6 mm):	0 – 91.3 m
HQ	(OD 88.9 mm, ID 77.8 mm):	0 – 145.3 m

Casing pulled out before abandonment

NOTE: Revised 14 March 2003