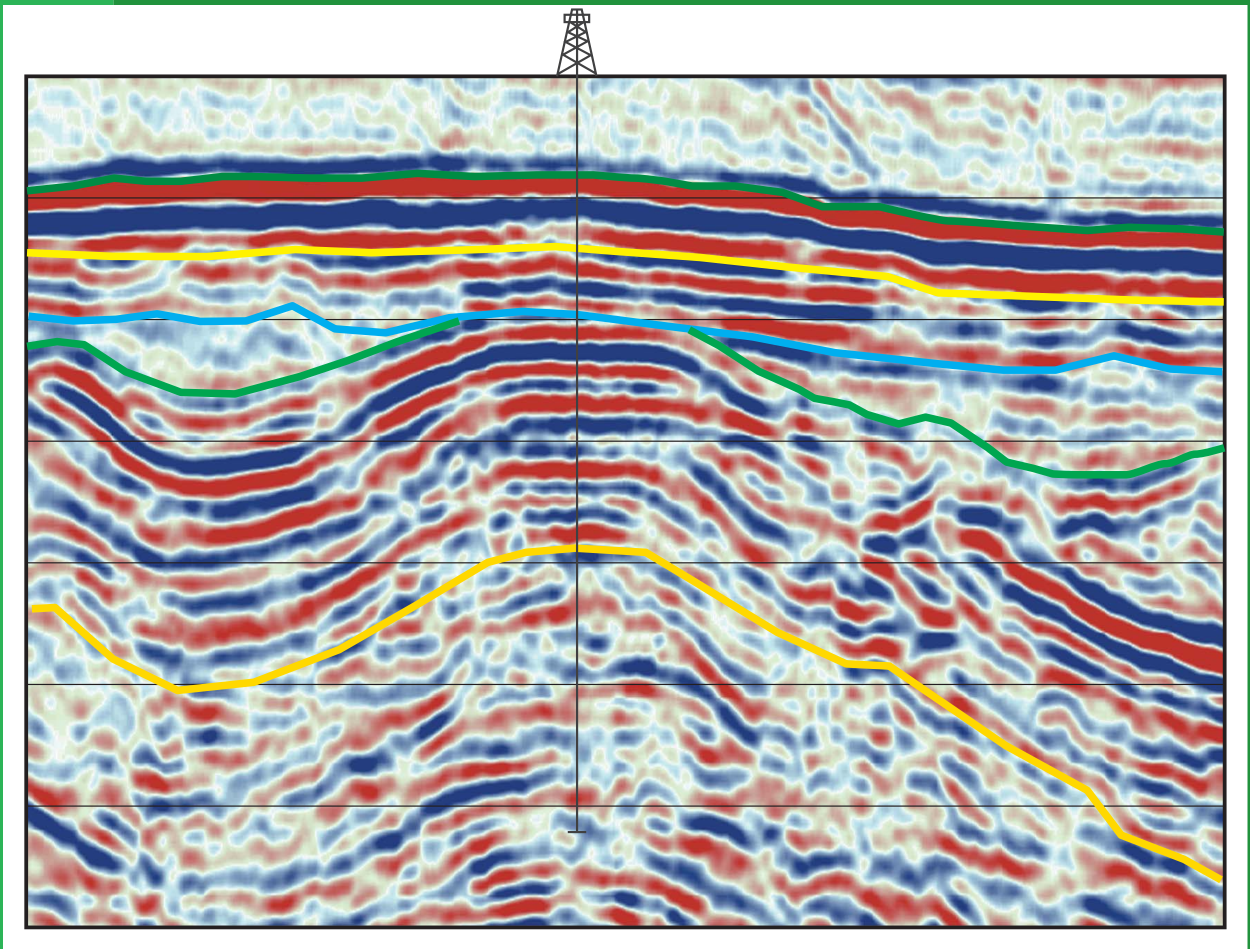
REPORT
76

GOVERNMENT OF
WESTERN AUSTRALIA

BASIN DEVELOPMENT AND PETROLEUM EXPLORATION POTENTIAL OF THE YOWALGA AREA, OFFICER BASIN WESTERN AUSTRALIA

by S. N. Apak and H. T. Moors



GEOLOGICAL SURVEY OF WESTERN AUSTRALIA

DEPARTMENT OF MINERALS AND ENERGY

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by
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Perth 2000

Copy editor: L. Day

REFERENCE
The recommended reference for this publication is:
APAK, S. N., and MOORS, H. T., 2000, Basin development and petroleum exploration potential of the Yowalga area, Officer Basin, Western Australia: Western Australia Geological Survey, Report 76, 61p.

National Library of Australia
Cataloguing-in-publication entry

Apak, Sukru N.
Basin development and petroleum exploration of the Yowalga area, Officer Basin, Western Australia.

Bibliography.
ISBN 0 7307 5649 1

1. Petroleum — Prospecting — Western Australia — Yowalga Sub-Basin.
2. Petroleum — Prospecting — Western Australia — Officer Basin.
3. Petroleum — Geology — Western Australia — Yowalga Sub-Basin.
4. Petroleum — Geology — Western Australia — Officer Basin.
5. Yowalga Sub-Basin (W.A.).
6. Officer Basin (S. Aust. and W.A.).
I. Moors, H. T. (Henry Theodore), 1942–.
II. Geological Survey of Western Australia.
III. Title. (Series: Report (Geological Survey of Western Australia); 76).

553.2809941

ISSN 0508–4741

Grid references in this publication refer to the Australian Geodetic Datum 1984 (AGD84)

Printed by Lamb Printers Pty Ltd , Perth, Western Australia

Copies available from:
Information Centre
Department of Minerals and Energy
100 Plain Street
EAST PERTH, WESTERN AUSTRALIA 6004
Telephone: (08) 9222 3459 Facsimile: (08) 9222 3444
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Basin development and petroleum exploration potential of the Yowalga area, Officer Basin, Western Australia

by

S. N. Apak and H. T. Moors

Abstract

This Report provides a new interpretation of the basin evolution, petroleum systems, and play types of the Yowalga area, using current methods of sequence stratigraphy based upon an analysis of the cores, logs, and seismic data in this region. The Lefroy Formation and Townsend Quartzite are interpreted as facies of a single depositional unit. During deposition of the Browne Formation, water depths, even in the bathymetric lows, were well above wave base. During deposition of the Hussar Formation, a very low-relief basinal setting persisted. Depositional environments and facies variations of the Kanpa Formation are similar to those of the Hussar Formation. The Steptoe Formation was deposited within a range of restricted shallow-marine shelf and low-energy, restricted shallow-marine or lagoonal depositional environments. The Lupton Formation is represented by diamictite, and massive and cross-bedded sandstone, and contains a thin 'cap dolomite' horizon in the uppermost part. The McFadden Formation represents a prograding delta to shallow-marine shelf depositional environment. Laterally correlatable genetic units, bounded by flooding surfaces and facies for each recognized unit, and derived largely from core information in the Empress 1 and 1A well, have been extrapolated laterally using wireline-log correlation with other wells. The region between Yowalga 3 and the Musgrave Complex was the most rapidly subsiding part of the Yowalga area, and the greatest depositional thicknesses accumulated here. Six conformable parasequence sets, bounded by flooding surfaces, have been identified within Sequence B. A total of five conformable parasequence sets bounded by flooding surfaces have been identified within Sequence H. In Sequence K, two conformable parasequence sets were deposited in shallow-marine to tidal- flat environments. Two parasequence sets deposited in prograding cycles on a low-relief ramp have been identified in Sequence S.

Recently acquired aeromagnetic data and reprocessed vintage seismic data have allowed more confident correlations and structural interpretations to be made. The Areyonga Movement produced the largest structures in the Yowalga area. These structures were later modified by halokinetic and additional structural events. The Musgrave Complex may have been a regional upland and the provenance for early coarse-grained clastics at the onset of Neoproterozoic deposition. Regional-scale uplift that began during the Areyonga Movement resulted in the total removal or non-deposition of Supersequence 2 rocks in the western Officer Basin. The Petermann Ranges Orogeny post-dates major glaciation during the Supersequence 2 and Supersequence 3 time frames. Sedimentation in the Officer Basin was terminated by global continental breakup and the extrusion of vast quantities of flood basalt over most of the depressions on the Australian plate.

A total of seven petroleum wells have been drilled in the Yowalga area. Oil and gas shows have been encountered in Browne 1, Browne 2, and Kanpa 1A. The stratigraphic test Empress 1 and 1A is a key well for the unravelling of the sedimentology of the Officer Basin. Good-quality oil-prone source rocks containing cyanobacteria and less abundant planktonic acritarchs have been identified. A variety of energy barriers in the generally shallow-water Officer Basin have been identified as sediment traps for organically enriched deposits. The scale of the basin prevented efficient water agitation and flushing from the ocean, so that even the shallow basins repeatedly became stratified and anoxic, except for their well-lit organically productive surface waters. A wide range of maturities has been found for potential source beds. Clastic reservoirs with 20% porosity and up to 1 D permeability have been identified. Most of the formations contain lithologies that would make effective seals at all scales. A wide range of possible structural and stratigraphic trapping configurations has been identified. Early traps were formed by the Areyonga Movement during the Neoproterozoic, whereas halokinetic deformation of Permian, Cretaceous, and Holocene rocks indicates a wide age range for potential traps. The ultimate petroleum potential of the Officer Basin still remains to be proven and may be very significant.

KEYWORDS: geological structures, stratigraphy, geochemistry, basin analysis, sequence stratigraphy, petroleum potential, basin geometry, Yowalga area, Officer Basin, Western Australia

Introduction

Although the Officer Basin (Fig. 1) is the third largest onshore basin in Australia, covering an area of 320 000 km^2 in Western Australia and having a sedimentary section in excess of 6 km, it is still poorly understood. Due to the volume of sedimentary rocks present and the significant proportion of carbonate rocks and salt, which are associated with prolific petroleum reserves in other parts of the world (Alsharan and Nairn, 1997; Warren, 1989), the petroleum potential of the basin has been regarded as high by recent workers (Perincek, 1997, 1998; Carlsen et al., 1999). Because of the early stage of evolution of organisms found in the Neoproterozoic, the absence of an adequate source rock for petroleum generation has been considered a high risk by the petroleum industry (Phillips et al., 1985). However, giant oil- and gasfields are known from rocks of this age in Russia (Kontorovich et al., 1990; Kuznetsov, 1997) and Oman (Alsharan and Nairn, 1997).

In an effort to encourage industry to realise the potential of the Officer Basin, the Geological Survey of Western Australia (GSWA) began a review of available data in 1994 (Perincek, 1997, 1998; Stevens and Carlsen, 1998), and supplemented this with additional data from corehole drilling, geophysical surveys, and geochemical analyses in critical areas (Carlsen et al., 1999; Fig. 2). The Yowalga area (Fig. 3) has the greatest amount of seismic and well control within the basin, and has been chosen as the first area to be studied in detail, in order to provide a useful template for other portions of the basin.

The Yowalga area coincides approximately with what has been defined as the Yowalga Sub-basin, based on potential-field data (Townson, 1985). However, where seismic data are available, there appears to be no evidence of an individual depocentre in this region. For this reason, the authors prefer to regard the region simply as the Yowalga area.

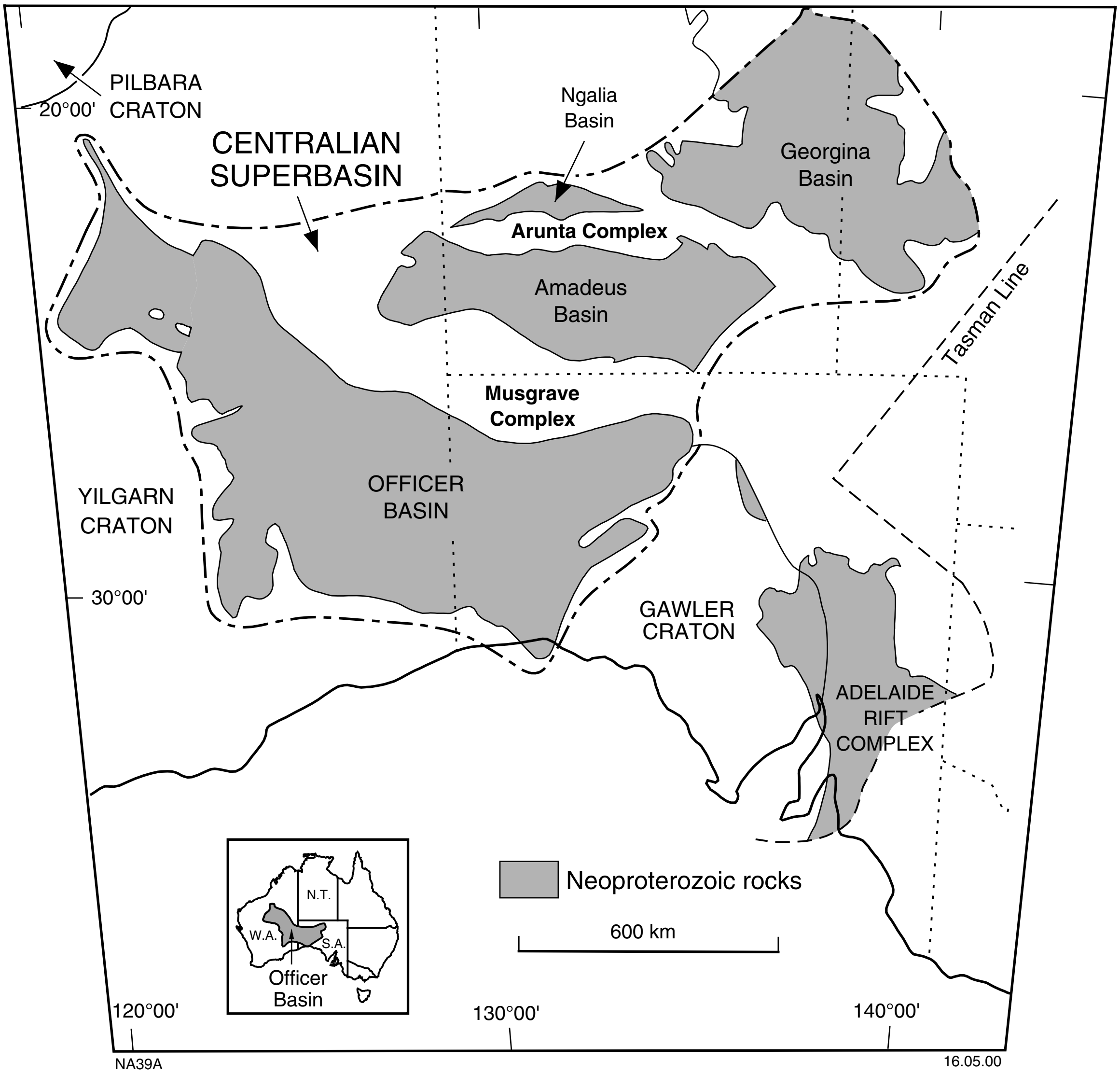


Figure 1. The Centralian Superbasin and constituent basins (after Carlsen et al., 1999)

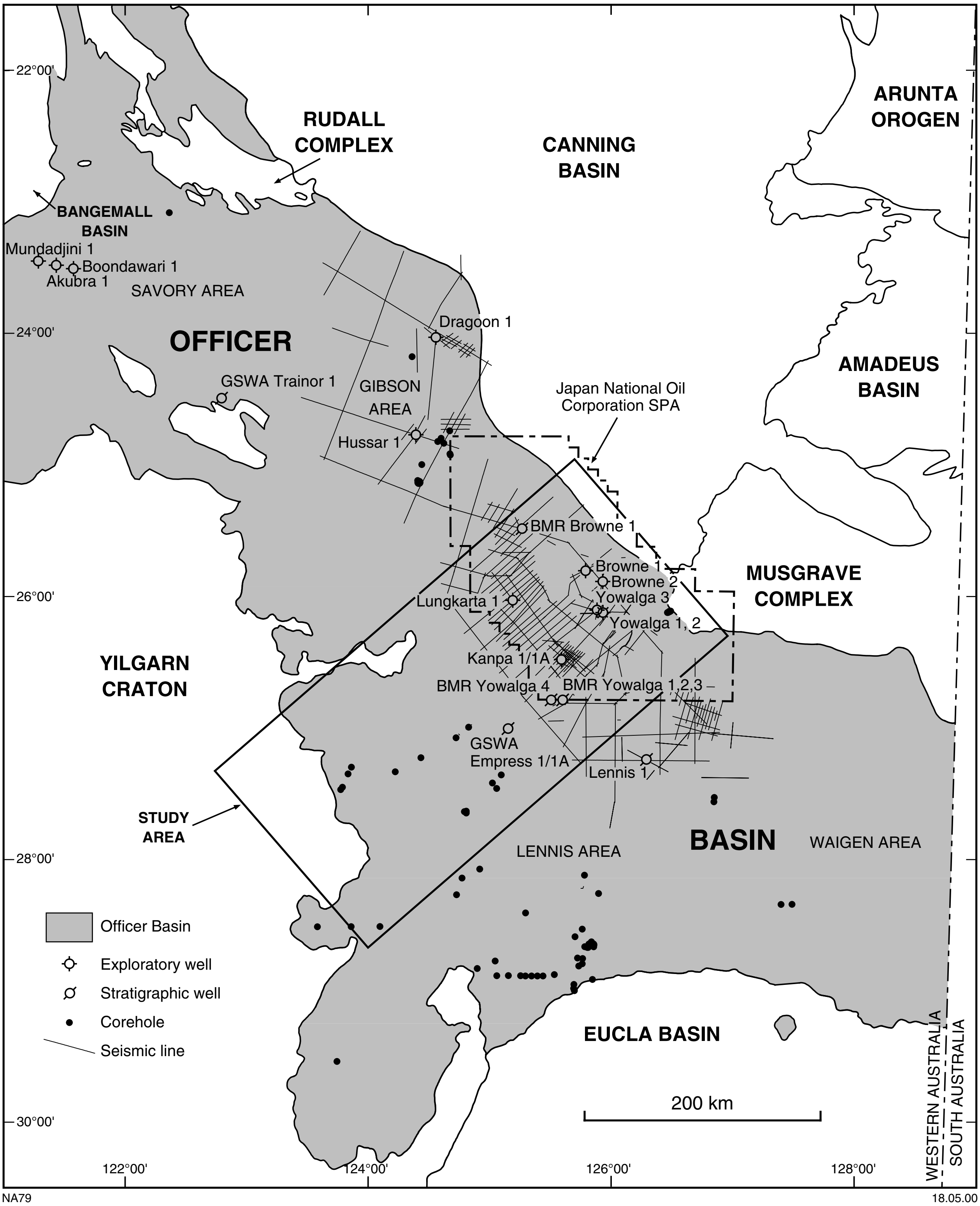


Figure 2. Location of petroleum exploration wells, stratigraphic tests, mineral exploration boreholes, and complete seismic coverage over the Officer Basin

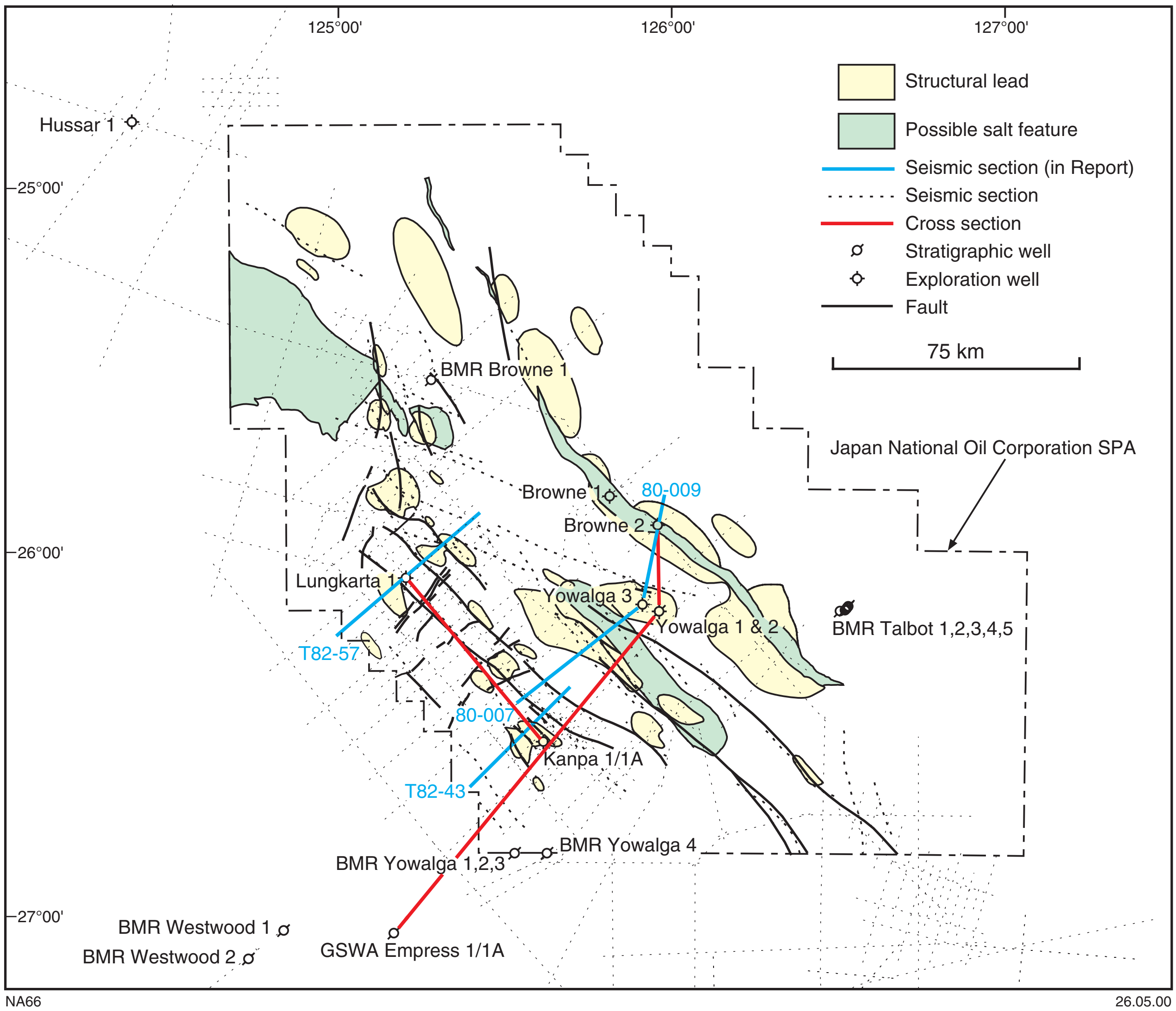


Figure 3. Location map showing seismic coverage and wells, and structures identified at the Top Browne level in the Yowalga area. Coloured lines refer to sections discussed in this Report

Sequence-stratigraphic concepts were employed to subdivide the Neoproterozoic strata into genetic units, which are of more use than traditional lithostratigraphic units in the evaluation of the petroleum potential of basins. The basic sequence concepts and terminology in this Report are based on the work of previous investigators such as Van Wagoner et al. (1990). In the Yowalga area, the dominant, shallow accommodation space has made it difficult to find evidence of the full range of depositional systems, such as lowstand, transgressive, and highstand systems. The sequence-stratigraphic units identified coincide closely with the previously defined lithostratigraphic subdivision (Townson, 1985). A minor modification has been made at the boundary of the Kanpa and Steptoe Formations in Kanpa 1A. The authors consider that the thick shaly horizons at the base of the Hussar, Kanpa, and Steptoe Formations represent major transgressional events at the base of new depositional cycles. This approach has resulted in a better understanding of the evolution of the basin, and has identified additional petroleum plays, as well as reducing the risk in predictions of the distribution of source rocks, reservoirs, and seals.

Previous investigations

Due to its isolation, difficult access, and relatively hostile environment, the Officer Basin initially received little geological attention. Petroleum exploration began in the early 1950s (Frome Broken Hill, Australasian Oil Exploration), but was mainly concerned with the Phanerozoic section of rocks. Early exploration activities relied mainly on surface mapping, until a consortium comprising Hunt Oil, Hunt Petroleum, Placid Oil, and Exoil was granted exploration permits in the 1960s. These companies acquired aerial and land magnetic data, gravity data, and 1033 km of seismic reflection data, and drilled five wells with a combined penetration of 2896 m. The deepest well, Yowalga 2, reached 989 m.

Due to the fact that only minor oil and gas shows were encountered (Browne 1 and 2; Hunt Oil Company, 1965), the tenements were dropped, but these investigations discovered salt diapirism in the area. The Bureau of Mineral Resources (BMR), now the Australian Geological Survey Organisation (AGSO), began to investigate these features in the 1960s. In 1967, GSWA started mapping the area as part of its statewide 1:250 000 mapping program, concentrating mainly on the Musgrave Complex (Daniels, 1974). In order to accelerate the mapping, a joint operation between GSWA and BMR was initiated (Bunting et al., 1978; Daniels, 1970, 1971; Jackson, 1976, 1978; Kennewell, 1977a,b). As well as surface mapping, gravity data and 19 line-km of seismic refraction data were acquired. In 1972, a series of short stratigraphic coreholes were drilled. All of these data were incorporated in a joint report on the Officer Basin (Jackson and van de Graaff, 1981).

As a result of this improved understanding, Shell Company of Australia acquired exploration permits in the Yowalga area. The company recorded 4682 line-km of seismic reflection data and drilled three deep wells, the deepest being Yowalga 3 to 4196 m. As a result of its investigations, the company divided the Officer Basin into sub-basins, improved the stratigraphic subdivision by adding additional formations, and discussed the basin development from the point of view of petroleum exploration (Townson, 1985). In the absence of significant shows, Shell Company of Australia relinquished its tenements.

The most recent investigation was carried out by Japan National Oil Corporation (JNOC), within a special prospecting authority (SPA No. 1/95–96) covering most of the Yowalga area. They flew a high-resolution aeromagnetic survey (86 782 km total length) and reprocessed 50 key seismic lines (2165 line-km). In addition, drill cuttings from wells in and around the Yowalga area were analysed for source-rock potential, and detailed thermal maturation histories were completed for the area. The SPA has now expired, and a report containing JNOC's* interpretations (Japan National Oil Corporation, 1997) is on open file at GSWA.

A more detailed review of the earlier phases of exploration, with statistics on drilling and geophysical and geochemical surveys, can be found in Perincek (1998) and Jackson and van de Graaff (1981).

Current GSWA investigation

The Officer Basin is being studied by GSWA as part of a Petroleum Exploration Initiative set up by the State Government of Western Australia in 1994, with encouragement from the petroleum industry, in order to investigate underexplored areas of the onshore basins.

The initial phase of the investigation comprised the collection of all open-file data on the Officer Basin, validation of the data, and an integrated reinterpretation. All of the seismic lines were reinterpreted, formation tops were repicked in all wells, and additional organic geochemical analyses were performed in key areas. Perincek (1996, 1997, 1998) has published a compilation and review of data pertaining to the hydrocarbon prospectivity of the Officer Basin. A fourth report (Stevens and Carlsen, 1998) covers the Savory Sub-basin only. Corehole drilling of Trainor 1 (Stevens and Adamides, 1998) and Empress 1 and 1A (Stevens and Apak, 1999) provided additional information for a fifth report (Carlsen et al., 1999) that concentrated on the petroleum potential of the basin, based on a new source-rock model from Empress 1 and 1A. This Report, the sixth report of the project, provides a more comprehensive examination of the seismic data (Table 1) and well logs (Table 2) in the Yowalga area (Fig. 3). The improved quality of the seismic data reprocessed by JNOC, and new sedimentological data provided by cores, coupled with a multidisciplinary approach, has allowed a new interpretation of the basin evolution, petroleum systems, and play types of the Yowalga area. The concepts established for the Yowalga area should be applicable throughout the remainder of the Officer Basin.

Location and access

The Yowalga area is a very remote and underpopulated region of Western Australia, and is 1250 km northeast of Perth. Nearby population centres include Cosmo Newbery, Warburton, Jameson, Blackstone, and Wingellina. There are no active pastoral developments in the area and infrastructure is therefore basic. Tourism is a significant industry, and a number of roads such as the Great Central Road, Emu Road, and parts of the Gunbarrel Highway (Fig. 4) are maintained. Sealed roadways end at Laverton, which is the last substantial town. The remaining roadways are unsurfaced roads of varying quality. Numerous roads and tracks constructed during mineral and petroleum exploration still exist and provide additional access.

Physiography, climate, and vegetation

The area generally lacks relief, with a drop in elevation from 600 m (Australian Height Datum) in the north to 450 m in the southwest. Ranges of Mesoproterozoic rocks border the basin to the north, forming the Warburton and Tomkinson ranges. Low elevation, laterite-covered scarps are present, and the lowland consists of calcrete tracts or laterally extensive dunefields, with dunes reaching 10–15 m in height.

The climate is arid, with an annual rainfall of 150–200 mm, which falls irregularly. The summertime maximum temperature ranges above 40°C between November and March, whereas during the winter months of June to August the minimum temperature commonly falls below 0°C.

Ground cover consists of spinifex and other grasses on the sandy soils, and the luxuriance of the vegetation increases on the dunes. A large range of shrubs are to be

* The permission of JNOC to use some of its interpretative figures in this Report is acknowledged.

Table 1. Seismic lines used in this Report

Line number	*Shotpoint range*
80-007	15 – 2 536
80-009	44 – 1 062
80-010	2 200 – 3 550
80-011	200 – 2 200
81-21A	1 – 1 600
T81-33	5 029 – 5 828
T82-33	5 769 – 6 809
T82-43	4 896 – 5 875
T82-56	4 335 – 5 473
T82-57	4 001 – 6 329

found between the grass and the open, stunted tree cover that is dominated by mulga. A range of other trees are scattered between the mulga, or in copses with favourable growing conditions (Jackson and van de Graaff, 1981; Daniels, 1970, 1971, 1974; Jackson, 1976, 1978; Kennewell, 1977a,b). Specific data on vegetative and climatic conditions are given by Beard (1974).

Stratigraphy

Poor outcrop, the limitations of Neoproterozoic biostratigraphy, and a sparsity of fossils make the establishment of a stratigraphy for the Officer Basin only tentative. Parts of the stratigraphic section are unknown in outcrop and have only been seen in well intersections, although they can be mapped from seismic data. Petroleum exploration has been the driving force in establishing the current stratigraphic nomenclature. The stratigraphy of the Officer Basin has been described by Jackson and van de Graaff (1981), Townson (1985), Phillips et al. (1985), Williams (1992, 1994), Perincek (1997), and most recently by Carlsen et al. (1999). Field studies and the analysis of Empress 1 and 1A core have established the stratigraphic relationship of the *Baicalia burra* and *Acaciella australica* Stromatolite Assemblages (Stevens and Apak, 1999), enabling the use of these common fossils as stratigraphic markers throughout the basin (Fig. 5). Carbon, oxygen, and strontium isotope measurements from this core have also provided additional correlation and relative dating tools (Stevens and Apak, 1999). Advances in acritarch biostratigraphy are also proving useful, and the determination of the absolute ages of various units, using radiometric dating, is helping to constrain the stratigraphic

Table 2. Well tops of units discussed in this Report

Well *S-series no.* *Company*	*Empress 1 and 1A* *20424* *GSWA*	*Kanpa 1A* *2281* *Shell*	*Lungkarta 1* *2667* *Shell*	*Yowalga 3* *1709* *Shell*	*Yowalga 2* *281* *Hunt Oil*	*Browne 2* *234* *Hunt Oil*
Samuel Formation	–	–	surface	surface	surface	surface
Paterson Formation	79	40	88	106	94.5	140
Lennis Sandstone	131	440	364	555	407	–
Table Hill Volcanics	201	547	540	763	728	–
McFadden Formation equivalent	–	658	704	–	–	–
Lupton Formation	286	–	–	–	–	–
Steptoe Formation	483	829	–	–	–	–
S2	–	829	–	–	–	–
S1	483	970	–	–	–	–
Kanpa Formation	617	1 341	809	880	846	–
K2	617	1 341	809	–	–	–
K1	748	1 472	859	880	846	–
Hussar Formation	860	1 817	1 196	991	nr	–
H5	860	1 817	1 196	991	nr	–
H4	981	2 020	1 400	1 267	nr	–
H3	1 030	2 140	1 578	1 485	nr	–
H2	1 065	2 220	1 682	1 617	nr	–
H1	1 105	2 259	1 722	1 655	nr	–
Browne Formation	1 250	2 515	nr	1 888	nr	262
B6	1 250	2 515	nr	1 888	nr	nr
B5	1 340	2 712	nr	2 228	nr	nr
B4	1 397	2 927	nr	2 650	nr	nr
B3	1 466	3 052	nr	2 950	nr	nr
B2	–	3 288	nr	3 320	nr	nr
B1	–	3 570	nr	3 744	nr	nr
Lefroy Formation	1 521	nr	nr	nr	nr	nr
Townsend Quartzite	–	3 671	nr	nr	nr	nr
Pre-Officer Basin (Mesoproterozoic)	1 540	nr	nr	nr	nr	nr
Total depth	**1 624.6**	**3 803**	**1 770**	**4 196.5**	**989**	**292.6**

NOTES: – formation/unit absent
nr not reached

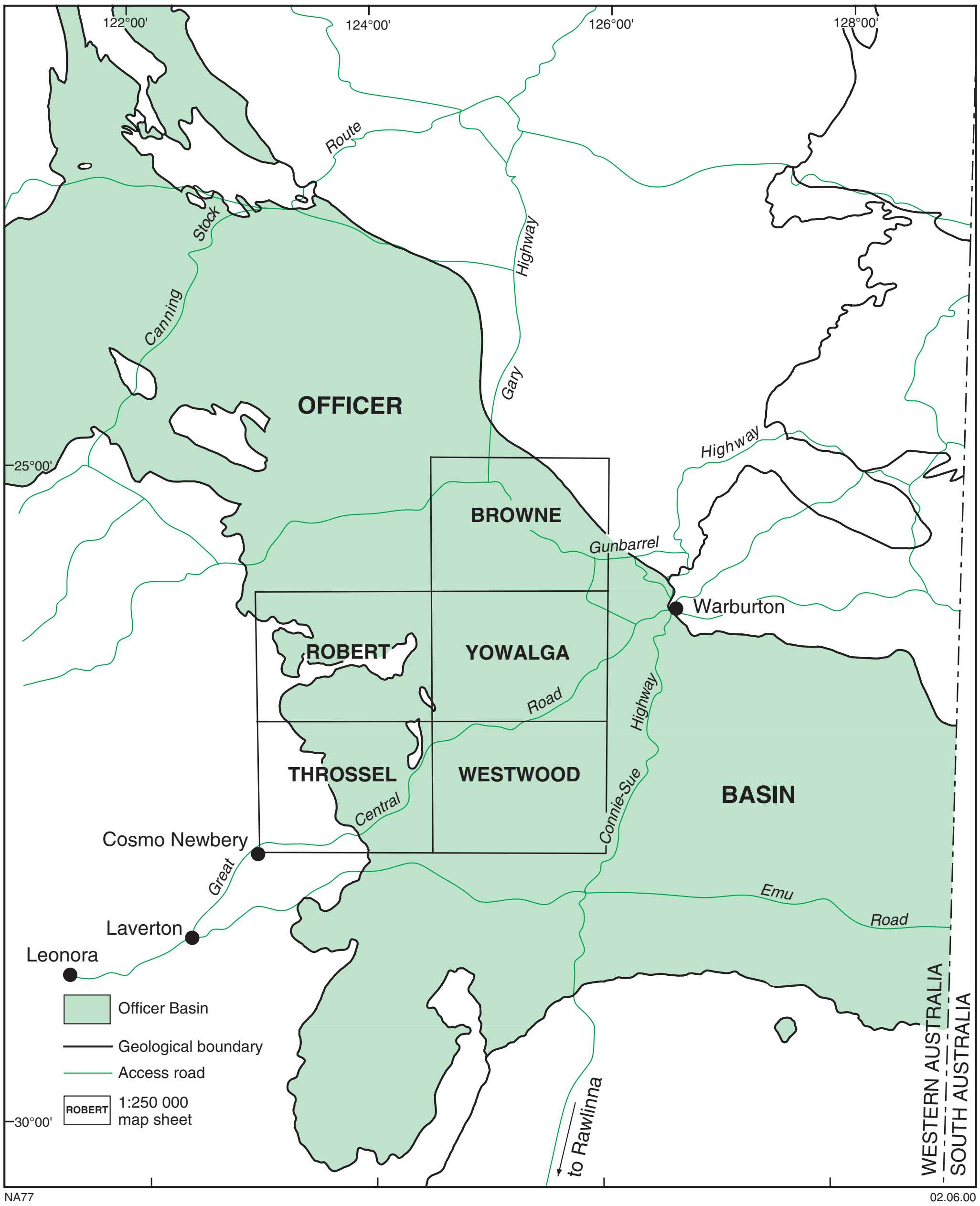


Figure 4. Access routes in the Officer Basin and the location of 1:250 000 map sheets

column (Stevens and Apak, 1999). However, it is expected that further changes will be made to formation and sequence tops.

The Officer Basin has been included as part of the Centralian Superbasin by Walter and Gorter (1994). They proposed that a single depositional system comprising the Amadeus, Ngalia, Georgina, and Officer Basins occupied an area of over two million km^2 of Australia during the Neoproterozoic. They also erected a series of supersequences for the Centralian Superbasin. However, usage of the term supersequence for these basins is inappropriate (Walter and Gorter, 1994; Perincek, 1998; Carlsen et al., 1999), but as a matter of convenience, and so as to provide continuity with previous authoritative papers, the supersequence terminology is used in this Report. Using current methods of sequence stratigraphy, the authors have also constructed a new subdivision of the Yowalga area stratigraphy that is based upon their analysis of the cores, logs, and seismic data for this region.

The stratigraphic column presented in Figure 6 is the authors' interpretation of the depositional ages of the sedimentary units and the intervening tectonic events present in the Officer Basin. Of current concern is the establishment of the chronological range and magnitude of the various tectonic phases described for the Officer and adjacent basins. Because drilling has not yet intersected a number of key stratigraphic units and tectonic events that are identifiable on seismic data,

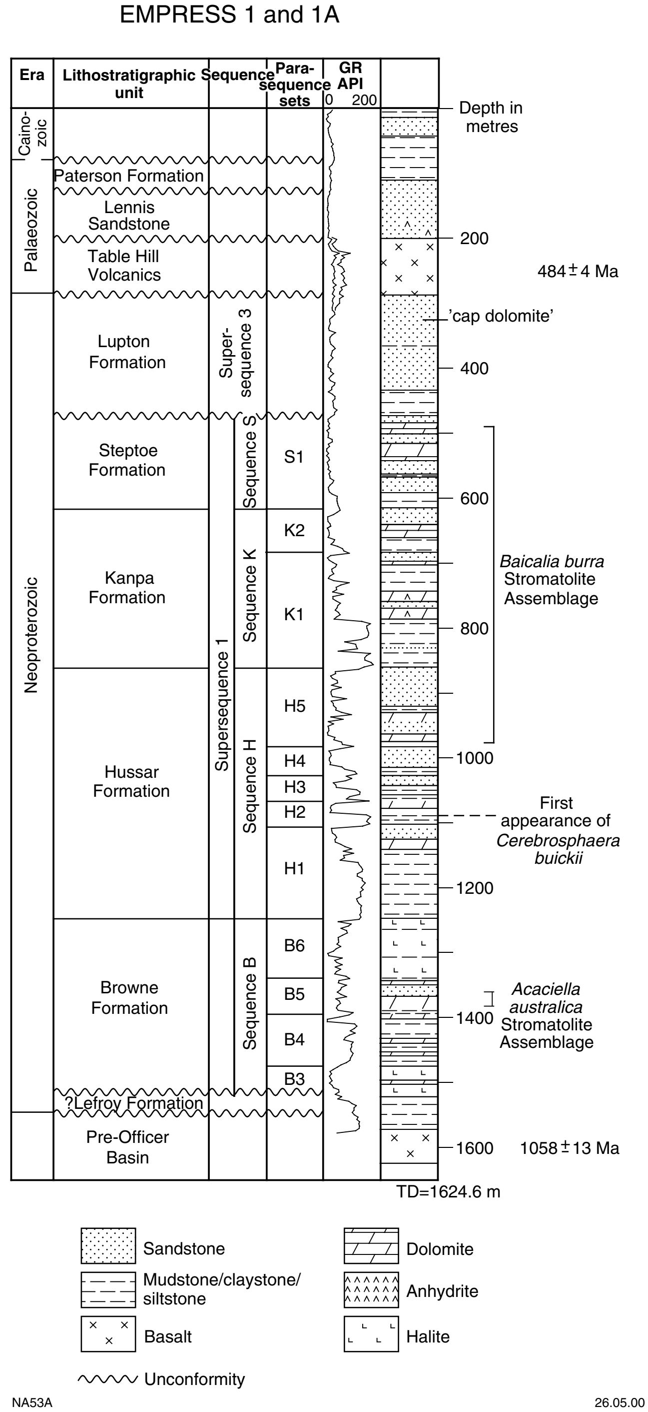


Figure 5. Empress 1 and 1A simplified composite log, showing sequence-stratigraphic units (modified from Carlsen et al., 1999)

this Report incorporates the chronological range established by conventional fieldwork. As new data become available, it is expected that further changes will be made for some of these events. Until a definitive chronology can be established for a unique set of structural phases affecting the Officer Basin, current studies will conform to the scheme used by the GSWA Petroleum Initiative over the past six years.

In Empress 1A, the potassium–argon age of continental flood basalt in the basement sequence is 1058 ± 13 Ma, and the age of the Table Hill Volcanics (also a continental flood basalt) is 484 ± 4 Ma (Stevens and Apak, 1999). These dates constrain the age of the Officer Basin in the Yowalga area, and contribute to age constraints for the entire Officer Basin. In addition, stable-isotope analyses were made on organic carbon and

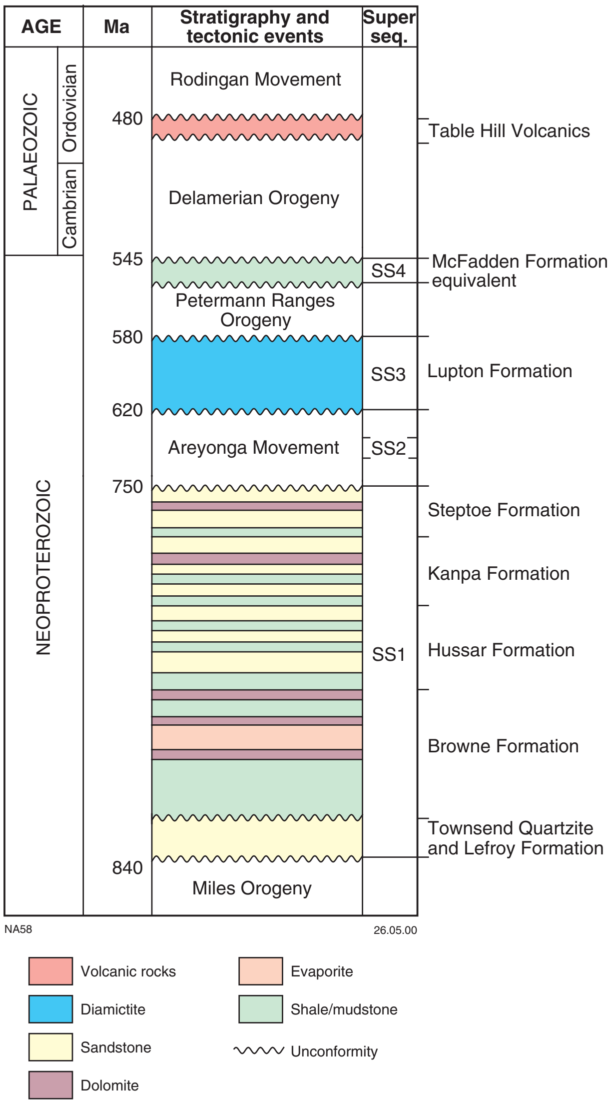


Figure 6. Generalized stratigraphy and tectonic events in the Yowalga area

carbonate carbon throughout the Empress 1 and 1A core, and a number of correlations were made to isotopic curves in other basins (Stevens and Apak, 1999). All of these age constraints have contributed to the stratigraphic subdivision of the Yowalga area.

New methods and additional data have been used to refine the chronostratigraphy and depositional model for the western Officer Basin. The Empress 1 and 1A core and the Yowalga area seismic data reprocessed by JNOC provided a powerful tool for the application of sequence-stratigraphic concepts in elucidating the architecture and development of the basin.

The geology of the Neoproterozoic and Early Palaeozoic strata capped by the Table Hill Volcanics is the main focus of this project. The following summary is derived from the authors' observations and those of the following authors: Jackson and van de Graaff (1981), Townson (1985), Phillips et al. (1985), Williams (1992, 1994), Perincek (1997), Carlsen et al. (1999), and Stevens and Apak (1999).

Neoproterozoic

Townsend Quartzite and Lefroy Formation

The study area includes the type locality and reference sections of the Townsend Quartzite and Lefroy Formation, as reported in Jackson and van de Graaff (1981). The Townsend Quartzite can be seen in outcrop to unconformably overlie the Musgrave Complex, where up to 370 m of fluvial to shallow-marine clean sandstone have been measured (Townson 1985). At the only outcrop of the Lefroy Formation, the Townsend Quartzite can be seen to grade conformably into the siltstone and shale of the overlying Lefroy Formation. There are no well intersections showing the Townsend Quartzite and Lefroy Formation in conformable contact. Of the two wells that penetrate the base of the Neoproterozoic rocks in the Yowalga area, only Kanpa 1A intersects the Townsend Quartzite. In Kanpa 1A, the Townsend Quartzite is disconformably overlain by the Browne Formation. In Empress 1A, the Lefroy Formation unconformably underlies the Browne Formation and unconformably overlies basement on the southwestern margin of the Officer Basin. In the authors' opinion, based on the well intersections and a single outcrop contact, the Townsend Quartzite and Lefroy Formation form a single depositional unit. The Townsend Quartzite represents a shallow-water facies, and the Lefroy Formation represents the deeper water facies of this single depositional unit.

The interpreted depositional environment for the Townsend Quartzite is fluvial to shallow marine (Daniels, 1974; Jackson and van de Graaff, 1981; Watts, 1982; Grigson, 1982). This indicates a deltaic association that provides a point of influx of coarse material into the basin. Daniels (1974) measured depositional-fabric current indicators and established that the provenance was from the north and northeast, and suggested the Musgrave Complex as the source area. The Lefroy and Browne Formations show an absence of sandstone, indicating a decrease in clastic supply and a deeper water origin for the Lefroy Formation.

The distribution of sandstone is important in assessing the reservoir potential of the Townsend Quartzite. The extent of the sandstone cannot be predicted at this stage of the program. There is no direct evidence to support the previous model of a single sandsheet forming a basal transgressive unit over the entire Centralian Superbasin, and this conclusion is not supported by the wells drilled in the Yowalga area. Sandstones are probably not as extensively distributed as suggested by models from adjacent basins and by previous investigations (Jackson and van de Graaff, 1981; Walter and Gorter, 1994; Walter and Veevers, 1997). The conclusion that the Lefroy Formation and Townsend Quartzite are facies of a single depositional unit provides for more bathymetric variation in the early depositional environment of the Yowalga area, and highlights the potential for source and seal horizons, as well as reservoirs, in this part of the succession.

Data on the Lefroy Formation is very sparse, being only available from outcrop and shallow drilling near the Musgrave Complex (BMR Talbot wells) and a possible short intersection in the Empress 1A corehole (Stevens and Apak, 1999). In Empress 1A, the ?Lefroy Formation, which contains a thin basal lag conglomerate, unconformably overlies the pre-Officer Basin section. Lithologies identified are quiet-water grey or maroon, well-bedded siltstone, claystone, and fine sandstone. The sequence in Empress 1A is correlated with the Lefroy Formation on lithostratigraphic grounds.

The Lefroy Formation was probably deposited in a similar, though slightly deeper water, environment to the overlying Browne Formation. This suggests a very extensive low-relief, low-energy basin where the creation of accommodation space was faster than deposition. Cessation of the deposition of the Townsend Quartzite and Lefroy Formation is indicated by signs of emergence and possible minor erosion in Empress 1A, which contains the only known exposure of the upper contact. The generally conformable Browne Formation represents a phase where deposition outpaced accommodation creation, thus resulting in facies that reflect frequent emergence. It is possible that the Lefroy Formation is a lateral equivalent of the sandy Townsend Quartzite, which may only be present near sediment delivery points such as deltas, with the remaining coeval sediment being claystone of the Lefroy Formation facies. This relationship remains to be proven.

Browne Formation

There is no outcrop of the Browne Formation in the Yowalga area. However, a subsurface sedimentary succession penetrated in Yowalga 3 and Kanpa 1A was identified as the Browne beds by Townson (1985). Jackson (1976) first named the evaporites in shallow wells on BROWNE* as the Browne Evaporites, but Yowalga 3 and Kanpa 1A provided the first significant intersections of this formation. The lower contact of the Browne Formation is disconformable with the ?Lefroy Formation in Empress 1A and the Townsend Quartzite in Kanpa 1A. Its upper contact is conformable with the overlying Hussar Formation, except in areas of diapiric intrusions, such as in Browne 1 and 2 where the Browne Formation is unconformably overlain by Palaeozoic or younger strata. The formation is intersected in Browne 1, Browne 2, Empress 1A, Kanpa 1A, and Yowalga 3, which has the thickest section (greater than 2308 m). The Browne Formation is predominantly composed of red shale and siltstone interbedded with stromatolitic dolomite, halite, minor anhydrite, and sandstone. Thick halite deposits are present in Empress 1A, Kanpa 1A, and Yowalga 3 (Fig. 7). Up to ten meters of thick, solid halite beds were cored in Empress 1A. Log signatures indicate the presence of much thicker halite beds, interbedded with thin silty and shaly horizons, in Yowalga 3 and Kanpa 1A (Fig. 7b).

The depositional environments and facies variations for the Browne Formation are illustrated in Figure 7. The Yowalga area was a region of low bathymetric relief with scattered depocenters (JNOC, 1997, enc. 14). Periodic transgressions, interpreted from wireline logs and cores, flooded various parts of the area, with the depocenter near Yowalga 3 most commonly being in an open-marine environment. Away from the main depocentre, the area experienced frequent emergence. Water depths, even in the bathymetric lows, were well above wave base. The *Acaciella australica* Stromatolite Assemblage has been identified in the dolomite of the Browne Formation in Yowalga 3 and Empress 1A.

Hussar Formation

The Hussar Formation does not outcrop in the Yowalga area. The name Hussar beds was proposed informally by Townson (1985), and later elevated to Hussar Formation by Cockbain and Hocking (1989). The Hussar Formation conformably overlies the Browne Formation, and is conformably overlain by the Kanpa Formation. The Hussar Formation was penetrated in Hussar 1, Kanpa 1A, Lungkarta 1, Yowalga 3, and Empress 1A. The greatest thickness of the Hussar Formation was penetrated in Yowalga 3 (897 m).

The formation is composed of sandstone, mudstone, dolomite, and minor evaporite, with locally developed conglomerate. It contains repeated progradational sedimentary cycles of shelf, shoreline, tidal flat, and fluvial deposits, with upward-coarsening shoreface sandstone deposits predominating. The depositional model and facies variations for the Hussar Formation are shown in Figure 8a. A similar very low-relief basinal setting is again proposed. Waterlevels nevertheless were constantly shallow, as some of the carbonate and shale intervals can be correlated over large distances (e.g. H2 in Fig. 8b). In Empress 1A, the dolomitic section contains the *Baicalia burra* Stromatolite Assemblage, as well as tentatively identified *Tungussia* form indet. and microbial lamination.

Kanpa Formation

The Kanpa Formation does not outcrop in the Yowalga area. The Kanpa beds were proposed informally by Townson (1985) for intersections in Shell Company of Australia's oil exploration wells Yowalga 3, Kanpa 1A, and Lungkarta 1, and later upgraded to formation status by Cockbain and Hocking (1989). The Kanpa Formation conformably overlies the Hussar Formation, and is conformably overlain by the Steptoe Formation in Empress 1 and 1A and Kanpa 1A. However, in Yowalga 3 and Lungkarta 1 the top of the Kanpa Formation is eroded. Where the Steptoe Formation is not present, the Kanpa Formation is overlain unconformably by post-Supersequence 1 strata.

The thickest penetrated section of the Kanpa Formation is in Kanpa 1A (516 m). The formation consists of dolomite, mudstone, shale, siltstone, and sandstone, with minor evaporite and chert. The predominant depositional setting is shallow marine to tidal flat, with

* Capitalized names refer to standard 1:250 000 map sheets, unless otherwise indicated.

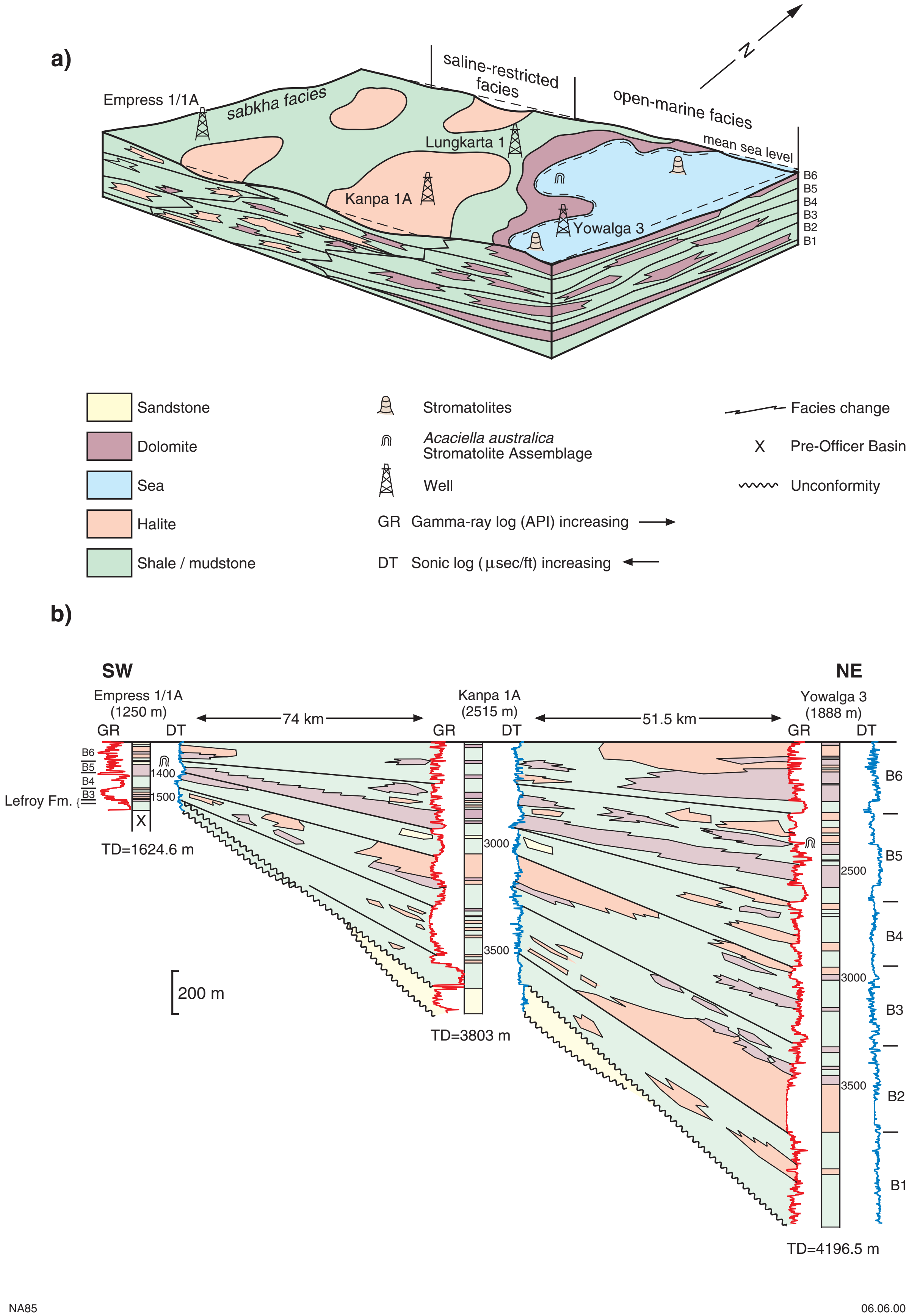


Figure 7. Interpreted depositional model for the Browne Formation: a) model showing a large, flat basin with numerous shallow ponds flooded during storms; b) sequence-stratigraphic correlation showing the lateral facies distribution between Empress 1 and 1A, Kanpa 1A, and Yowalga 3

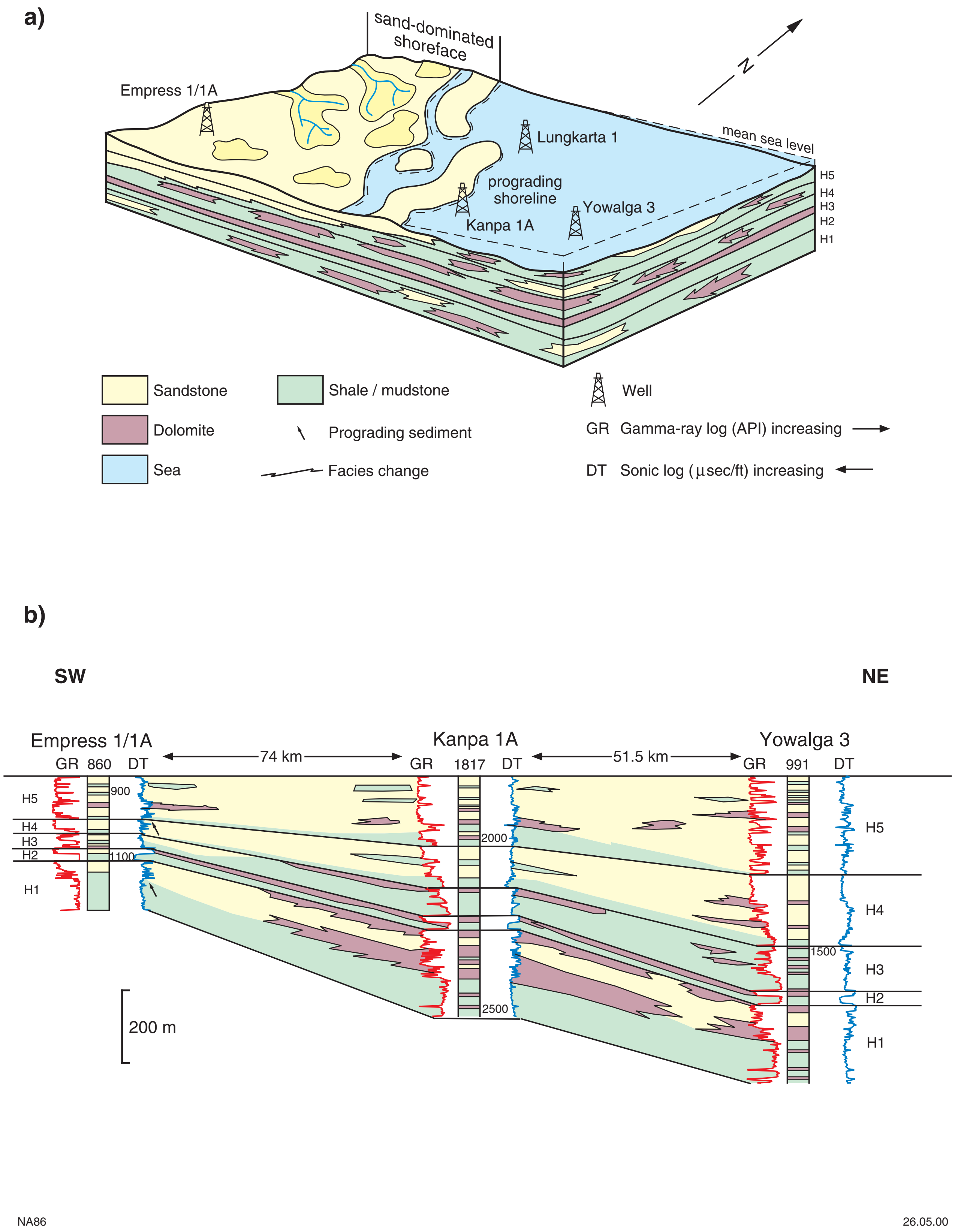
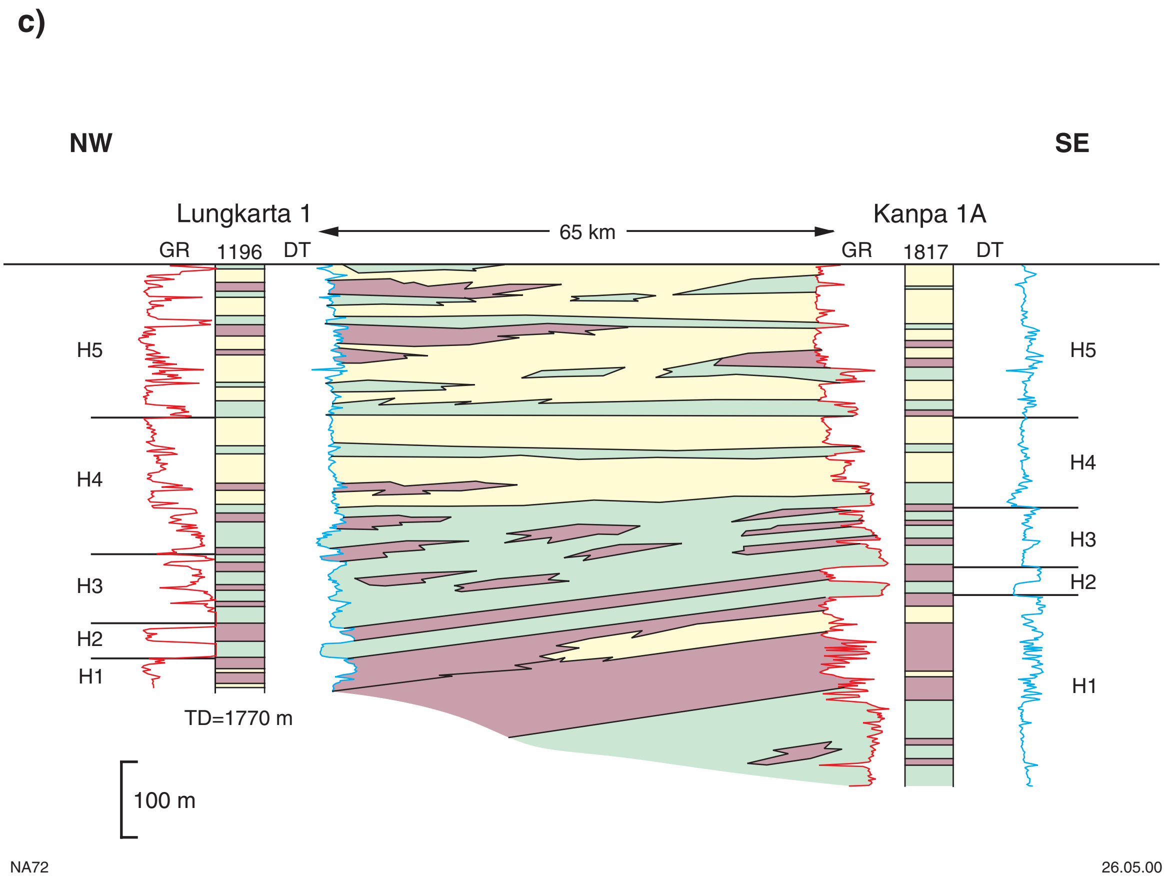


Figure 8. **Depositional model for the Hussar Formation: a) model showing a very low relief basinal setting with multiple prograding carbonate and siliciclastic cycles. Note that the younger successions H4 and H5 are dominated by upward-coarsening siliciclastic deposits; b) sequence-stratigraphic correlation showing the lateral facies distribution between Empress 1 and 1A, Kanpa 1A, and Yowalga 3; c) (facing page) sequence-stratigraphic correlation showing the lateral facies distribution between Lungkarta 1 and Kanpa 1A**



carbonate deposited in oxidizing to slightly reducing conditions. The interpreted depositional environments and facies variations for the Kanpa Formation, which are shown in Figure 9, are similar to those of the Hussar Formation. The depositional environment was a gentle ramp sloping to the northeast towards the Yowalga 3 area. Depositional cycles of shallow-marine carbonate and sandstone can be correlated between the two formations, and appear to be a function of sea level changes. Sabkha facies were locally developed during regressive phases (see **Sequence stratigraphy**). In Empress 1 and 1A, dolomite commonly contains stromatolites of the *Baicalia burra* Stromatolite Assemblage, and mudstone units contain abundant cyanobacterial filaments and fragments of cyanobacterial mat, together with the probably planktonic acritarch *Cerebrosphaera buickii*, a key species in this stratigraphic interval.

Steptoe Formation

The Steptoe Formation does not outcrop in the Yowalga area. The name Steptoe beds was proposed informally by Townson (1985) for a unit penetrated in Kanpa 1A, and later upgraded to formation status by Cockbain and Hocking (1989). In the Empress 1 and 1A well completion report, the Steptoe Formation was combined with the Kanpa Formation, but in this Report it is considered to have valid formation status. The Steptoe Formation conformably overlies the Kanpa Formation. The upper boundary of the Steptoe Formation is an erosional unconformity with the overlying McFadden Formation equivalent in Kanpa 1A (Perincek, 1997), and with the overlying Lupton Formation in Empress 1 and 1A. In the study area, the Steptoe Formation was penetrated by Kanpa 1A (472 m) and Empress 1 and 1A (132 m). However, it has been eroded entirely from the Lungkarta 1, Yowalga 3, and Browne 1 and 2 structures, and has been partly eroded in Empress 1 and 1A during the Areyonga Movement and Petermann Ranges Orogeny (Plate 1, Fig. 9).

In Kanpa 1A, the Steptoe Formation consists of dolomite, mudstone, claystone, and sandstone. In Empress 1 and 1A, above the claystone-dominated basal transgressive deposits, the Steptoe Formation consists of sandstone, mudstone, loose sand, and dolomite. The Steptoe Formation was deposited within a range of restricted shallow-marine shelf and low-energy, restricted shallow-marine or lagoonal depositional environments. The dolomite contains stromatolites of the *Baicalia burra* Stromatolite Assemblage, including *Tungusia wilkatana* in Empress 1 and 1A (Stevens and Apak, 1999).

Lupton Formation

Outside the study area, the Lupton Formation outcrops at Lupton Hills and along the southern edge of the Musgrave Complex. Around the type section at Lupton Hills, the formation consists of massive conglomerate, with scattered boulders and sandstone interbedded with siltstone and

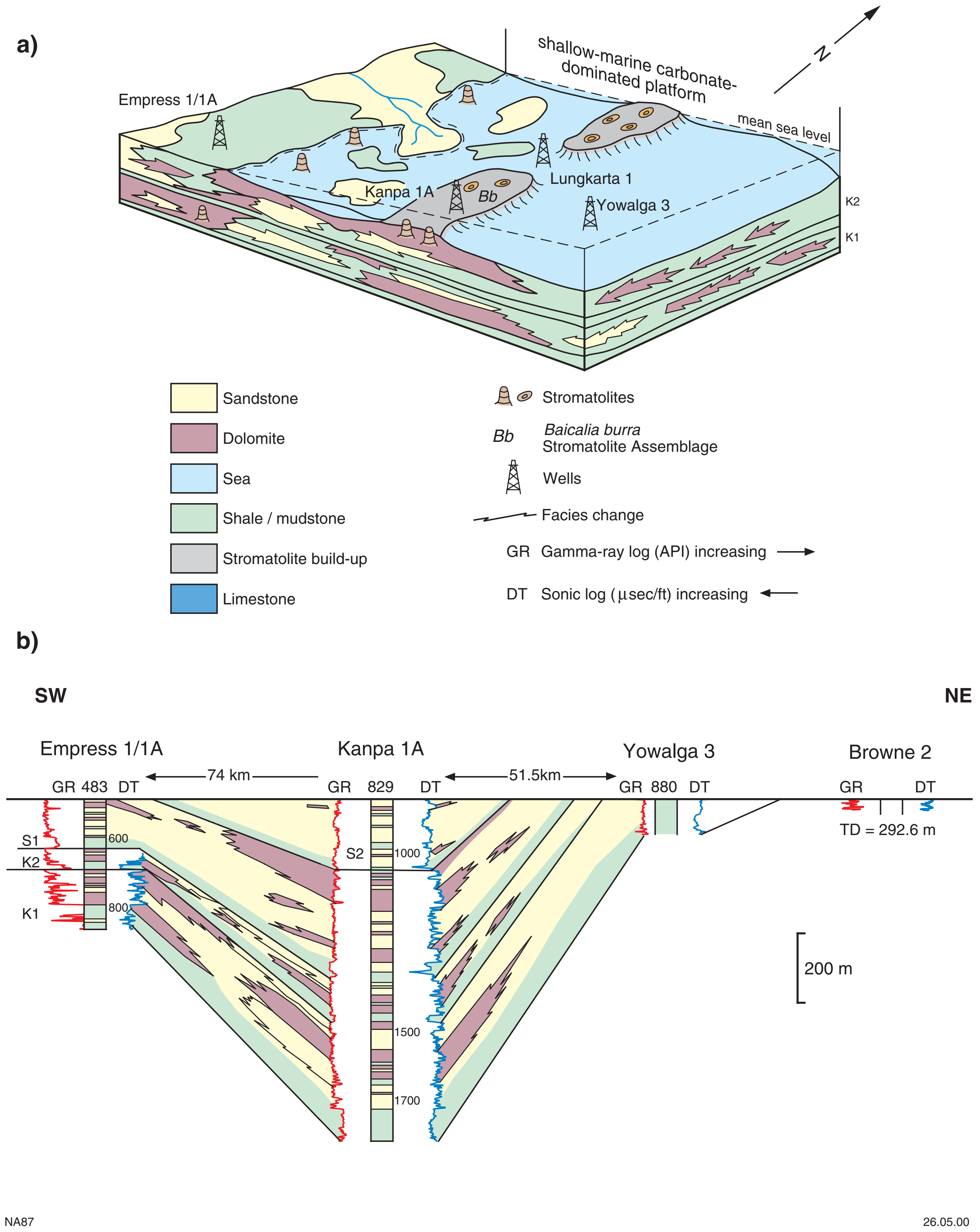
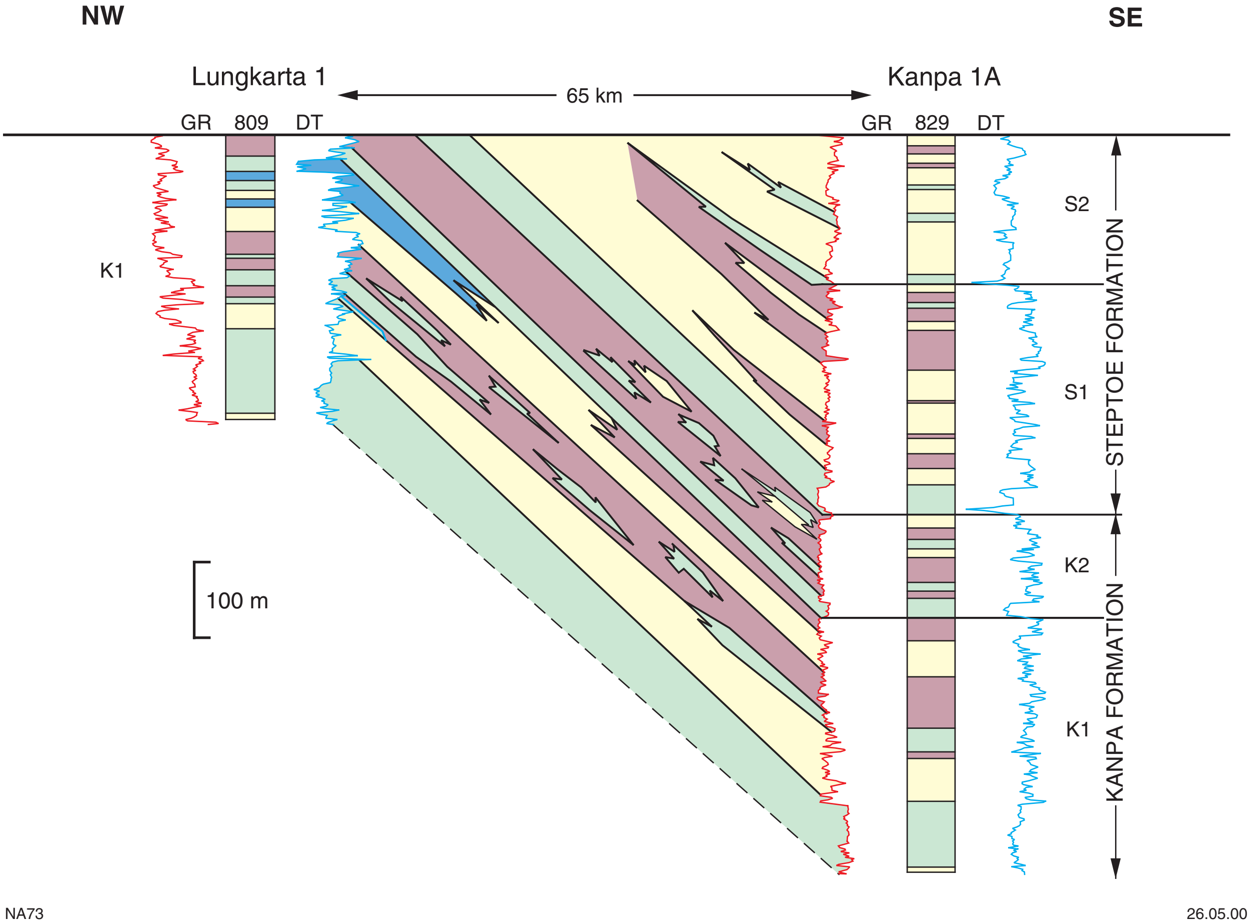


Figure 9. Depositional model for the Kanpa and Steptoe Formations: a) model showing carbonate and siliciclastic deposits within shallow-marine to lagoonal and sabkha type of environments; b) sequence stratigraphic correlation showing the lateral facies distribution between Empress 1 and 1A, Kanpa 1A, and Yowalga 3; c) (facing page) sequence-stratigraphic correlation showing the lateral facies distribution between Lungkarta 1 and Kanpa 1A

c)



diamictite. The Lupton Formation unconformably overlies the Lefroy Formation. In Empress 1 and 1A, it unconformably overlies the Steptoe Formation, and is unconformably overlain by the Table Hill Volcanics. In this well, the Lupton Formation is 166 m thick and is represented by diamictite, massive and cross-bedded sandstone, and contains a thin dolomitic horizon in the uppermost part. This dolomitic horizon has been interpreted to be equivalent to the 'cap dolomite' that forms the top of the Marinoan glacial strata in the Amadeus Basin and Adelaide Rift Complex (Grey et al., 1999; Preiss et al., 1978). The unnamed Supersequence 3 sandstone unit that overlies the cap dolomite of the Lupton Formation with a gradational contact (Stevens and Apak, 1999) is considered to be part of the Lupton Formation in this study.

McFadden Formation equivalent

This unit was intersected in Hussar 1, Kanpa 1A, and Lungkarta 1, and was previously interpreted as the Babbagoola Formation (Townson, 1985; Phillips et al., 1985). It is separated from both the underlying and overlying units by seismically identifiable unconformities (Townson, 1985; Perincek, 1997). Perincek (1997) correlated the unit to the McFadden Formation, which outcrops in the Savory Sub-basin. In this study, seismic data confirmed that the unit, which was penetrated by the three wells mentioned above, is laterally equivalent to the McFadden Formation of the Savory Sub-basin. Empress 1 and 1A did not intersect this unit. The McFadden Formation consists of medium- to coarse-grained sandstone, and minor shale and siltstone, and represents a prograding delta (Perincek, 1997) to shallow-marine shelf depositional environment.

Palaeozoic

Table Hill Volcanics

Extrusion of the Table Hill Volcanics marked the beginning of a new depositional sequence that has been formally assigned to the Gunbarrel Basin (Hocking, 1994). The Table Hill Volcanics can be seismically correlated over a large area of the western Officer Basin, and outcrops on the northeastern margin of the basin, near the southwestern margin, and in the Waigen Sub-basin near the South Australian border. It consists of porphyritic and amygdaloidal tholeitic basalt. Ages of 575 ± 40 Ma (Compston, 1974) or Middle – Late Cambrian (Moussavi-Harami and Gravestock, 1995; Perincek, 1997) have been proposed for the unit. However, K–Ar radiometric dating in Empress 1A (Stevens and Apak, 1999) indicates an Early Ordovician age of 484 ± 4 Ma. In the context of the petroleum potential of the area, the remaining Palaeozoic units in the Gunbarrel Basin are only important in the calculation of thermal maturation, and in the analysis of the diagenetic changes undergone by units in the Officer Basin. The stratigraphy of the other Gunbarrel Basin units is not discussed in this Report.

Sequence stratigraphy

Wireline logs, core data, palaeontological data, isotope data, and seismic-facies analyses have been utilized to provide a sequence-stratigraphic framework for the Neoproterozoic sedimentary successions in the Western Australian portion of the Officer Basin. The main aims were: 1) to describe the types of sedimentary deposits in the Yowalga area; 2) to show the major controlling factors for their distribution; and 3) to develop depositional models that will enable the prediction of potential areas where reservoirs, seals, source rocks, and traps may be present.

The basic sequence concepts and terminology applied in this study follow those of Van Wagoner et al., (1990) and Galloway (1989). Basin analysis requires the broad-scale reconstruction of three dimensional depositional systems in relation to concurrent structural development of the basin. For this reason, in this study emphasis is given specifically to the discussion of depositional systems, seismic facies analysis, and regional tectonic models.

The authors' interpretation of wireline logs and seismic data throughout the Yowalga area demonstrates the presence of laterally correlative genetic units bounded by flooding surfaces. Four deep petroleum-exploration and numerous stratigraphic wells have been correlated and tied to seismic data (Figs 7b, 8b and c, 9b and c, Plate 1). Well and seismic correlation in this low-gradient depositional environment are based on extensive, defined transgressional events. These major transgressional deposits can be seismically correlated across the study area (Apak and Moors, 2000). They are taken as a horizontal datum to establish lateral facies variations within the Neoproterozoic successions. Secondary transgressions, observed on seismic data as high-amplitude reflections with good continuity, are also used for further subdivision to define parasequence sets. From the available data, sequence-variation controls are unclear. These variations could be due to sea level changes or to structural processes at a local or tectonic scale, or a combination of these.

Regionally, the top of the Browne Formation produces a decrease in acoustic impedance at its conformable boundary with the overlying Hussar Fomation. Internal reflections within the Browne Formation are not regionally extensive, due to lateral facies variations from claystone to dolomite to evaporite, which includes halite and anhydrite. Reflection amplitude commonly falls below ambient noise levels, thereby preventing confident seismic correlations through lateral facies variations. The tops of the Hussar and Kanpa Formations are defined as peaks of middle-amplitude reflection, due to the differential acoustic impedance between the Hussar and Kanpa Formations, and between the Kanpa and Steptoe Formations. High-amplitude intraformational reflections with good continuity suggest the presence of laterally correlative lithologies within the Hussar, Kanpa, and Steptoe Formations. The Steptoe Formation has been eroded to varying degrees (Empress 1 and 1A) and is completely missing in most wells in the study area (Yowalga 3, Lungakarta 1, Browne 2; Figs 9b and c, Plate 1). The basal flooding event in some interpreted parasequence sets is responsible locally for minor erosion of the underlying unit in marginal areas. These erosional contacts, as observed in Empress 1 and 1A, are not considered large enough in vertical relief, time scale or areal extent to constitute sequence boundaries. The Table Hill Volcanics is characterized as a high-amplitude reflection, with excellent continuity throughout the study area (Plate 1).

The facies interpretation for each recognized unit is derived largely from core information in the Empress 1 and 1A well, and is extrapolated laterally to other wells, using wireline-log correlation. Where stratal units are not represented by core in Empress 1 and 1A, facies have been interpreted by the comparison of log signatures. The following section focuses on the stratigraphy of the Browne, Hussar, Kanpa, and Steptoe Formations, but only in those areas with adequate well control.

Neoproterozoic

Sequence B (Browne Formation)

Sequence B (Browne Formation) is widespread in the study area, as well as in the western Officer Basin, but it has been eroded on the crests of many folds, salt-cored structures (diapiric salt), and on the northern margin of the basin, except along the Anketell – Warri Gravity Ridge (Carlsen et al., 1999). The narrow range of facies variations, from shallow marine to sabkha, in the Browne Formation indicates gentle regional subsidence, and balance between sediment input and creation of accomodation space. Poor resolution of subsalt seismic data, and a lack of wells fully penetrating the Browne Formation, make it difficult to define any local structural control of deposition. The presence of major salt walls, apparently controlled by the post-depositional structure, may indicate fault trends that were active episodically, such as those formed during the Areyonga Movement. There is no direct evidence from cores, wireline logs, or seismic data to indicate syndepositional faulting. The region between Yowalga 3 and the Musgrave Complex was the most rapidly subsiding part of the Yowalga area, and the greatest depositional thicknesses of the formation accumulated here (Fig. 7b).

Based on an integrated approach, a total of six conformable parasequence sets, bounded by flooding surfaces, have been identified within Sequence B (Fig. 7). These are numbered sequentially B1 to B6, from the base upwards. The two lower parasequence sets (B1 and B2) are limited to the Yowalga 3 area, although the upper part of B1 has been identified in Kanpa 1A. The overlying younger parasequence sets (B3–B6) are widespread in the study area. The facies description and interpreted depositional environment for each sequence-stratigraphic unit is given below.

B1

The deposition of B1 was limited to the vicinity of Yowalga 3, where it is 452 m thick. Deposition here may represent infilling of remnant basement topography, as no syndepositional faulting is indicated by the wireline logs or seismic data. Yowalga 3 reached total depth in the Browne Formation, and seismic interpretation suggests an additional unknown thickness of the formation in this region. The basal portion of B1 is missing in Kanpa 1A, and the entire parasequence set is absent from Empress 1A. These areas were not transgressed during deposition of B1, and the upper section of the Browne Formation rests unconformably on the Lefroy Formation, Townsend Quartzite, or on pre-Officer Basin units. In Yowalga 3, B1 consists of silty, anhydritic, dolomitic shale interbedded with halite, and in Kanpa 1A it consists of evaporitic shale and siltstone. Based on lithological characteristics interpreted from the well-log data, B1 was deposited in a sabkha to hypersaline lagoon or restricted shallow-marine environment (Fig. 7b).

B2

As subsidence became more widespread, deposition of B2 covered a larger area. Deposition was still mainly limited to the central part of the study area and did not reach the marginal areas to the southwest, where Empress 1A is located. In Yowalga 3, B2 consists of predominantly halite, silty dolomitic and anhydritic shale, and dolomite, with a total thickness of 424 m. B2 is 235 m thick in Kanpa 1A and consists of similar lithologies to Yowalga 3. The presence of thicker anhydrite beds in Kanpa 1A suggests that the area was probably on the margin of a restricted platform or hypersaline lagoon environment (Fig. 7b).

B3

During the deposition of B3 the basin continued to widen. The maximum penetrated thickness of B3 is 470 m in Yowalga 3 (Fig. 7b). B3 thins to the southwest, where the penetrated thickness is 236 m in Kanpa 1A, and 55 m in Empress 1A, where only the upper portion is present. B3 consists of siltstone, mudstone, halite, dolomite, and sandstone. In Yowalga 3 and Kanpa 1A, the lower portion of B3 consists of silty shale (mudstone) interbedded with minor dolomite. This portion is interpreted as being deposited in a very shallow, low-energy marine environment. The upper portion of B3 consists of a halite-dominated facies in Kanpa 1A and Empress 1A, and predominantly mudstone, siltstone, and minor dolomite and halite beds (in the uppermost part) in Yowalga 3. This indicates the presence of a sabkha to restricted hypersaline, shallow-water environment towards the southwest (Kanpa 1A to Empress 1A), in contrast to a very shallow marine, partly carbonate-dominated environment around Yowalga 3, which was drilled in the deeper portion of the basin (Fig. 7b).

B4

B4 exhibits a relatively uniform thickness in the Yowalga area, although it thins gradually towards Empress 1A. It consists of predominantly argillaceous siltstone, minor dolomite, and halite deposits in Yowalga 3 (200 m); mudstone, siltstone, halite, and minor evaporite in Kanpa 1A (125 m); and predominantly mudstone in Empress 1A (69 m). The interpreted depositional environment is similar to the underlying successions in that it changes from a sabkha to hypersaline lagoon environment in the southwest, to a shallow-marine environment at Yowalga 3 (Fig. 7b).

B5

Continued gentle subsidence throughout the study area resulted in widespread deposition of B5. The thickness of B5 is 422 m in Yowalga 3, 215 m in Kanpa 1A, and 57 m in Empress 1A. Above the basal transgressive horizon, the lower part of B5 consists of dolomite with minor siltstone in Yowalga 3; dolomite, shale, and minor anhydrite beds in Kanpa 1A; and dolomite, shale, siltstone, and sandstone in Empress 1A. In these wells, the upper part of B5 consists of predominantly halite deposits. Halite is interbedded with minor siltstone in Yowalga 3, with dolomite and shale in Kanpa 1A, and with shale in Empress 1A. The *Acaciella australica* Stromatolite Assemblage has been identified within the dolomite of this succession in Yowalga 3 (Grey, 1995) and Empress 1A (Grey, 1999). The presence of the *Acaciella australica* Stromatolite Assemblage within B5 reflects the remarkable similarity of depositional facies throughout the western Officer Basin (Carlsen et al., 1999).

B5 is interpreted as representing a prograding cycle, from a carbonate-dominated, very shallow marine environment to a sabkha to hypersaline restricted lagoon or shallow-marine environment (Fig. 7b).

B6

B6 has a thickness of 350 m in Yowalga 3, 197 m in Kanpa 1A, and 90 m in Empress 1A. In Yowalga 3, B6 consists predominantly of oolitic dolomite with minor argillaceous siltstone, anhydrite, chert, and halite, which is particularly prominent in its upper portion. The dolomite-dominated lithology is restricted to Yowalga 3. Towards the southwest, dolomite gradually decreases and halite becomes the predominant lithology within B6 in Kanpa 1A and Empress 1A (Fig. 7b).

As in the underlying B5, the lithological characteristics of B6 indicate a high-energy, shallow-marine carbonate environment in Yowalga 3, and a sabkha to restricted hypersaline, shallow-water environment in Kanpa 1A and Empress 1A.

Depositional environments

The first depositional cycle in Sequence B began with a basal transgression that can seismically only be partially correlated, due to the presence of salt in the formation. Abrupt increases in gamma-ray log response are indicative of increased amounts of mudstone and shale in these basal transgressive units. These transgressions are overlain by dominantly shallow-water facies in Yowalga 3, and sabkha to restricted hypersaline, shallow-water facies in the southwestern area near Empress 1A. These overlying units most likely represent highstand-system tract deposits. The presence of abundant halite and anhydrite deposits within the Browne Formation indicates changes in water salinity throughout deposition. Restricted circulation and evaporation have resulted in extensive deposition of evaporites in the basin (Fig. 7).

These sedimentary facies imply deposition in a restricted inland sea (or lagoon), with long periods of warm, dry climate under hypersaline and oxidizing conditions that are indicative of the low latitude of the area at that time (Baillie et al., 1994). The similarity in the characteristics of the sedimentary facies throughout the study area indicates that the rate of sedimentation generally kept pace with the accommodation space during deposition of the Browne Formation. The rate of subsidence was greater in the Yowalga 3 area, where deposition originally began. It later extended to other parts of the basin.

Sequence H (Hussar Formation)

A total of five conformable parasequence sets, bounded by flooding surfaces, have been identified within Sequence H. Minor erosional surfaces at the top of some cycles in Empress 1A suggest that these cycles probably represent type 2 ramp-margin deposits (Van Wagoner et al., 1990) that generally thicken towards the north-northeast.

H1

The thickness of the H1 parasequence set is 233 m in Yowalga 3, 256 m in Kanpa 1A, and 145 m in Empress 1A. Lungkarta 1 was terminated within the uppermost part of H1. H1 began with a regionally correlative major transgression, and conformably overlies B6. In Yowalga 3, this basal transgressive deposit consists of argillaceous siltstone with minor dolomite and sandstone, with similar lithologies in Kanpa 1A and Empress 1A. The upper part of the unit consists of dolomite, which in places is interbedded with sandstone and minor mudstone, as seen in Yowalga 3 and Kanpa 1A. However, in Empress 1A the upper portion of H1 is dominated by shoreface sandstone, suggesting some clastic input by a fluvial system at this location. Due to the great distance between Empress 1A and Kanpa 1A, clastic input had less influence on the carbonate deposition to the northeast (Figs 8b and c).

Overall, thick basal transgressive deposits gradually pass upward into shallow-marine carbonate deposits in the central area, and sandstone-dominated shoreface deposits towards the marginal areas. This parasequence set is interpreted as an upward-shallowing cycle terminated by a regional flooding event.

H2

H2 is the thinnest depositional cycle in the Hussar Formation, and is interpreted as a single parasequence that is mappable throughout the Yowalga area. It is about 40 m thick in Yowalga 3, Kanpa 1A, Lungkarta 1, and Empress 1A. It is conformable with both the underlying and overlying parasequence sets, although a locally erosive surface exists between H 2 and the overlying H 3 in Empress 1A. H2 is characterized by basal transgressive argillaceous siltstone and mudstone, which is transitionally overlain by dolomite throughout the entire study area (Figs 8b and c). Lithological characteristics of the dolomite in Empress 1A, Kanpa 1A, and Yowalga 3 indicate a shallow-marine, probably tidal-influenced, carbonate depositional environment. The dolomite contains the *Baicalia burra* Stromatolite Assemblage and microbial lamination. In Empress 1A, the siltstone contains the first appearance of *Cerebrosphaera*. Identical lithologies, as interpreted from cuttings and wireline logs, are present in the other wells (e.g. Kanpa 1A and Yowalga 3).

H3

Parasequence set H3 also began with a basal transgressive horizon that consists predominantly of argillaceous siltstone to mudstone. H3 is 132 m thick in Yowalga 3, 104 m in Lungkarta 1, 80 m in Kanpa 1A, and 35 m in Empress 1A. In Yowalga 3, which is the northernmost well, H3 consists of interbedded siltstone and mudstone with minor dolomite and anhydrite beds, whereas in Kanpa 1A it consists of mudstone and dolomite. In Empress 1A, the basal mudstone facies grades into an overlying shoreface sandstone. The shoreface sandstone facies changes laterally to shallow-marine carbonate in other areas. Vertical and lateral facies associations indicate that the area where Empress 1A is now located subsided at a slower rate than other parts of the basin during this period (Figs 8b and c).

H4

In the Yowalga area, parasequence sets H4 and H5 conclude the Hussar depositional series with two repeated sandstone-dominated shoreface successions. H4 is 218 m thick in Yowalga 3, 120 m in Kanpa 1A, 178 m in Lungkarta 1, and 49 m in Empress 1A. Thin interbeds of mudstone within the shoreface sandstone deposits probably represent minor transgressions of short duration. The presence of local erosional surfaces in Empress 1A further suggests that units are condensed in marginal areas (Figs 8b and c).

H5

The uppermost parasequence set of Supersequence H varies from sandstone at the base, to carbonate, and then back to sandstone in the upper part of the unit. These facies are interpreted to have been deposited in the same shallow-marine environment. H5 is 276 m thick in Yowalga 3, 203 m in Kanpa 1A, 204 m in Lungkarta 1, and 121 m in Empress 1A. Particularly in Empress 1A, H5 can easily be subdivided into thin parasequences (Figs 8b and c).

Depositional environments

Sequence H contains multiple progradational phases of shelf, shoreline, tidal flat, and fluvial deposits, with upward-coarsening shoreface sandstone deposits predominating. These depositional units are laterally extensive, and can be confidently correlated in detail in all four deep-well intersections (Plate 1, Fig. 8). These stacked cycles imply transgressive and regressive cycles on a low-relief, ramp-like basinal setting over most of the area. Each parasequence set shows upward-shoaling characteristics, and they are interpreted as regressive or prograding shoreface deposits (Fig. 8).

The dark-grey mudstone at the base of each parasequence set in Empress 1A is interpreted as reflecting deposition in a quiet environment below storm wave base (Stevens and Apak, 1999). Thick, widespread shale and mudstone deposits indicate rapid and widespread transgression, suggesting a relative rise in sea level that resulted in increased sediment accommodation space. Rapid transgression sometimes resulted in erosion of the underlying unit. Sandstone horizons commonly exhibit sharp upper and lower surfaces, and represent high-energy depositional events in a shoreface to lower shoreface, shallow-marine environment, as is clearly evident in the Empress 1A core. They are interbedded with and overlain by laminated to thinly bedded shelf to lagoonal mudstone facies.

Regional lateral- and vertical-facies associations indicate that deposition was continuous in the Yowalga area, and was primarily progradational in nature. There is no evidence for any significant tectonic movement during this time, although thinning of some of the successions towards the southwest suggests minor syndepositional faulting or regionally variable rates of subsidence.

Sequence K (Kanpa Formation)

Two conformable parasequence sets can be observed in Sequence K in Kanpa 1A and Empress 1A (Figs 9b and c). Erosional truncation of these parasequence sets, interpreted from seismic data, indicates deposition over an area larger than present-day limits. Seismic uniformity of the interval indicates that these units can possibly be predicted to extend laterally beyond the Yowalga area.

K1

K1 is 111 m thick in Yowalga 3, 345 m in Kanpa 1A, 37 m in Lungkarta 1, and 112 m in Empress 1A (Figs 9b and c). K1 has a uniform thickness between Kanpa 1A and Lungkarta 1, whereas it gradually thins towards the Empress 1A area, and is mostly eroded in Yowalga 3. This basal parasequence set began with a thick transgressive deposit that can be correlated laterally over most of the Yowalga area.

In Empress 1A core, the basal transgressive section is predominantly mudstone that is interbedded with wave-rippled silty to sandy beds. Small-scale stratal truncation along bedding surfaces indicates scouring and minor erosion. Based on a study of the Empress 1A core (Stevens and Apak, 1999), the basal section of K1 is interpreted as a low-energy facies that was probably deposited in a shallow-marine environment. Above the transgressive section, K1 is composed mainly of stromatolitic dolomite interbedded with mudstone and minor evaporite. Lithological characteristics, and broken and sharply truncated stromatolites, indicate frequent periods of emergence that resulted in rapid facies changes from a high-energy carbonate platform to a low-energy, shallow-marine environment (Figs 9b and c).

Above the basal transgressive section in Kanpa 1A, K1 consists of mixed lithologies such as sandstone, dolomite (in part anhydritic), siltstone, and chert, indicating frequent sea-level fluctuations in shallow-marine to sabkha depositional environments. In Lungkarta 1, 65 km northwest of Kanpa 1A, the lithology of K1 is similar to that found in Kanpa 1A.

K2

K2 is present in Kanpa 1A, Lungkarta 1, and Empress 1A (Figs 9b and c). It is 131 m thick in Kanpa 1A and Empress 1A and, due to erosion, only 50 m of the basal portion is preserved in Lungkarta 1. It is entirely eroded in Yowalga 3.

In Empress 1A and Kanpa 1A, K2 reflects a dolomite-dominated depositional cycle, with interbedded sandstone layers above the basal mudstone deposits. Based on core data from Empress 1A, the dolomites are stromatolitic, and some of the stromatolites are broken and truncated by erosion, and this erosive surface is abruptly overlain by mudstone.

Depositional environments

The Kanpa Formation was deposited over most of the Officer Basin. Cross sections in this Report (Fig. 9) show the widespread deposition of the Kanpa Formation over the study area. Lithological characteristics of the Kanpa Formation, such as interbeds of parallel-laminated and wave-rippled mudstone, sandstone, and carbonate, indicate shallow-marine to tidal-flat environments of deposition. In the Kanpa 1A area in particular, thicker sandstone beds and coarser grain size indicate a close proximity to a shoreline for K1. This suggests sea level fluctuations that caused occasional erosive contacts with the overlying mudstone or shale throughout deposition. Basin-wide progradation of transgressive systems was repeated throughout deposition of the Kanpa Formation. The fact that the basin was still subsiding during the deposition of the Kanpa Formation is shown by the pronounced thickening of the basal succession in the area from Empress 1A to Kanpa 1A.

As a result of the uplift and erosion that took place from the Areyonga Movement to the Petermann Ranges Orogeny, the Kanpa Formation was folded and faulted, and was subjected to significant erosion in the Yowalga 3 area, where only a very thin part of the basal transgressive section remains (Fig. 9b).

Sequence S (Steptoe Formation)

Two parasequence sets of the Steptoe Formation have been identified in Kanpa 1A (S1 and S2), but these parasequence sets can not be correlated with confidence to Empress 1 and 1A, where a condensed section is present.

S1

S1, the lower unit of Sequence S, is 371 m thick in Kanpa 1A and 134 m thick in Empress 1 and 1A. As in the underlying units, the deposition of S1 began with correlative basal transgressive deposits dominated by claystone. In Empress 1 and 1A, S1 consists predominantly of sandstone, mudstone, loose sand, and stromatolitic dolomite that contains the *Baicalia burra* Stromatolite Assemblage. The dolomites are massive, and include laminated micrite and sandstone beds with gravel-size dolomite clasts. In this well, many of these beds have sharp contacts (Stevens and Apak, 1999), suggesting erosion during sea level changes.

In Kanpa 1A, S1 consists predominantly of sandstone in the lower part, and dolomite in the upper part. The dolomite is partly oolitic, silty, and anhydritic. Well logs and the lithological characteristics of S1 indicate a prograding cycle on a low-relief, ramp-like depositional setting throughout the study area. In Kanpa 1A and Empress 1 and 1A, shallow-marine carbonate and sandstone deposits are dominant in S1 (Figs 9b and c).

S2

In Kanpa 1A, S2 is 200 m thick. It consists predominantly of massive shale at the base, and sandstone interbedded with shale and anhydritic dolomite above. S2 is absent from the other wells in the study area due to erosion (Figs 9b and c).

Being the youngest depositional unit, the Steptoe Formation underwent the most severe erosion from the time of the Areyonga Movement to the Petermann Ranges Orogeny. In many places, erosion also removed the underlying Kanpa Formation, for example in the Yowalga 3 area. In Empress 1 and 1A, S2 is missing and the uppermost part of S1 has been extensively karstified, which suggests a significant lacuna following the deposition of Supersequence 1 in the Yowalga area.

Geophysics

Geophysical coverage of the Yowalga area includes gravity, magnetic, and seismic surveys as listed in Perincek (1998). In this Report, comment is provided on the usefulness of the various methods, and how they have contributed to an understanding of this part of the Officer Basin.

The Officer Basin was first identified as Neoproterozoic (Nullagine) in age by Utting et al. (1955), following reconnaissance geological mapping for Australasian Oil Exploration. Additional fieldwork and acquisition of potential-field data by the oil industry and BMR, as early as 1954, led to the identification of a number of sub-basins. Oil exploration in the early 1960s led to a number of additional aeromagnetic and gravity surveys. Unfortunately, in many cases, the gravity and magnetic data did not concur. This is partially due to the character of the basement, which is variably composed of igneous, metamorphic, and overmature sedimentary rocks.

Stratigraphic drilling provided information on the density and magnetic susceptibility of the Officer Basin strata and basement, thus enabling better geophysical models to be generated and more valid estimates of depth to basement to be made (Shevchenko and Iasky, 1997). Seismic surveys and deeper drilling provided additional control points. However, simple potential-field solutions have proven to be model dependent, and after stratigraphic drilling substantial adjustments have had to be made to such depth-to-basement maps.

In 1996, JNOC reprocessed and reinterpreted most of the available seismic data (JNOC 1997). The improvement in the seismic data was dramatic, and these reprocessed lines have been used in this study. Because of the geographically limited seismic coverage, JNOC acquired a high-resolution aeromagnetic and radiometric survey in order to extend modern geophysical coverage across their entire Special Prospecting Authority. JNOC's additional aeromagnetic information has also been incorporated in this Report.

Seismic data

The seismic data for the Yowalga area was used extensively in this study, in order to determine the structural framework of the area and to ascertain the stratigraphic architecture of the area. Initially, the same seismic horizons as previously interpreted by Perincek (1996) on the original seismic data, and mapped by JNOC (1997) from the reprocessed seismic data, were reinterpreted. These seismic horizons were as follows:

- Top Table Hill Volcanics
- Base McFadden Formation equivalent
- Top Kanpa Formation
- Top Hussar Formation
- Top Browne Formation
- Top acoustic basement

Maps of these interpreted horizons are contained in the JNOC (1997) report.

These seismic horizons, with the exception of the Top Browne and top acoustic basement, have mainly good continuity in the study area. Stratigraphic relationships of the formations and their sequential subdivisions are shown in Figures 6, 7b, 8b and c, and 9b and c.

The top acoustic basement, Top Steptoe Formation, Base McFadden Formation equivalent, and Top Table Hill Volcanics horizons all form unconformities with adjacent strata, whereas the Browne, Hussar, Kanpa, and Steptoe Formations conformably overlie each other (Fig. 6). The bases of the Hussar, Kanpa, and Steptoe Formations represent major transgressions in the study area, as well as over most of the western Officer Basin.

Data coverage

Shell Company of Australia and News Corporation conducted seismic surveys from 1980 to 1984 (Townson, 1985; Phillips et al., 1985), but seismic coverage over most of the western Officer Basin remains sparse. The Yowalga area has the most seismic data in the basin. The seismic facies interpretation was mainly carried out using the reprocessed lines submitted by JNOC (1997).

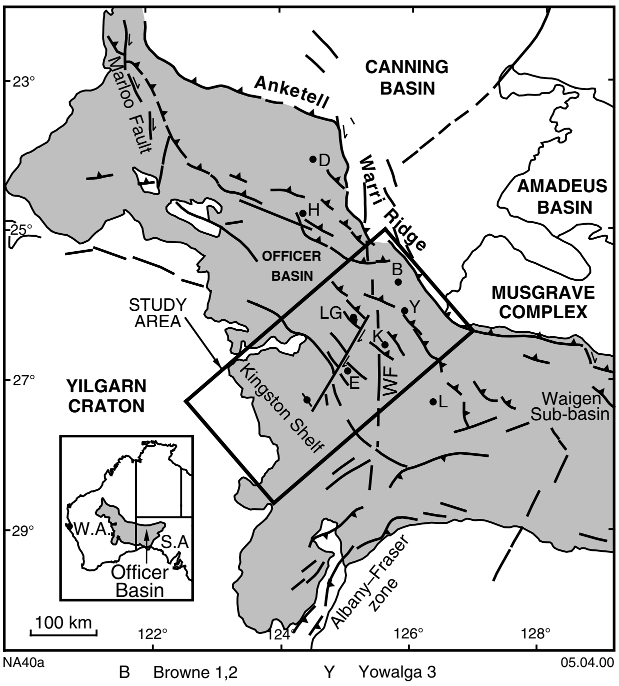
Data quality

The original quality of the seismic data for most of the basin is poor (Perincek, 1997). In this project, both the seismic data as processed by Shell Company of Australia and the JNOC reprocessed lines have been used. A comparison of the data quality before and after reprocessing shows a significant improvement in the resolution and continuity of reflections, thus allowing better interpretations using the reprocessed seismic lines. Strong-amplitude events that represent the major unconformities (e.g. Table Hill Volcanics) and transgressive surfaces can be correlated with confidence, although they are discontinuous in some places, mainly due to salt emplacement and complex faulting. The reprocessed seismic data (JNOC, 1997) are now on open file.

Aeromagnetic interpretation

To complement the seismic coverage, JNOC commissioned World Geoscience Corporation (WGC) to fly a high-resolution aeromagnetic and radiometric survey, and to image and model the magnetic structure using modern computer algorithms of WGC's own design. In an effort to constrain the interpretation, magnetic-susceptibility data on the various formations present were collected from cuttings in the Hussar 1, Kanpa 1A, Lungkarta 1, and Yowalga 3 wells. The Table Hill Volcanics was specifically targeted as having the highest susceptibility. A number of cross sections, created from seismic data, were modelled, and the modelled magnetic profile was compared to the measured values until there was a close match. The Werner technique (modified by WGC) was used for depth control, and proved accurate when compared to seismic data. A Euler deconvolution was also employed, but was not regarded as reliable as the Werner-derived depths (WGC, 1997).

Using their own algorithms, WGC was able to construct pseudo-depth maps for the Table Hill Volcanics event, a deeper intra-Browne Formation event, and magnetic basement. Using the magnetic data, WGC was also able to identify areas with anomalous salt thicknesses and indicate the presence of salt walls in addition to those identified on seismic data. Numerous igneous dykes were easily identified and mapped using the aeromagnetic data. Maps showing details of this interpretation are presented in WGC (1997).



B Browne 1,2
D Dragoon 1
H Hussar 1
E Empress 1/1A
K Kanpa 1A
L Lennis 1
LG Lungkarta
Y Yowalga 3
WF Westwood Fault
Normal fault
Inferred fault
Thrust fault
Drillhole

Figure 10. Simplified structural elements of the Officer Basin

Structural interpretation

Townson (1985) identified four major fault and lineament trends, based mainly on aeromagnetic, gravity, and Landsat interpretations. Of these faults, northwesterly, northeasterly, and northerly trending faults appear to be the major structural features in the study area (Fig. 10). The northwesterly trending faults are dominant. They parallel major faults in basement outcrops of the Musgrave Complex (Leven and Lindsay, 1995) and major regional anomalies in the potential-fields dataset, and are interpreted to have been formed by the reactivation of older basement structures. This fault trend is also reflected in the major salt-associated thrusting. The northeasterly trending faults have resulted from right-lateral strike-slip movement, and have displaced the northwesterly trending faults (Perincek, 1997). The northerly oriented faults, such as the Westwood Fault, are associated with dykes, and display post-Miocene offset that indicates reactivation of these faults. Townson (1985), Phillips et al. (1985), Perincek (1996, 1997), and JNOC (1997) have discussed the structure of the western Officer Basin in detail.

The structural history of the Officer Basin is complex, and has been affected by a number of regional events (Fig. 6). Major structures were established in the basement rocks before Neoproterozoic deposition began (Myers et al., 1996). During subsequent tectonic events, deformation in the Officer Basin was at least partially controlled by these basement structures. The main thrust that affected the basement lies to the east, and none of the Neoproterozoic tectonic phases were particularly severe in the Yowalga area. The major regional structures identified are salt walls and smaller salt-cored anticlines or thrust ramp folds. Except in association with salt piercement features, folding is gentle, with low dips, and is the composite product of a number of phases of tectonic movement.

Faulting

The most common type of faults in the Yowalga area are thin-skinned, listric thrust faults that are detached along saliferous horizons within the Browne Formation. They originate as flat thrusts low in the Browne Formation, and cut upsection along gentle curves to a more vertical orientation through the more competent overlying beds (Plate 1). Most of the displacement is confined to the Supersequence 1 strata, with minor reactivation extending the faults into younger units (Supersequences 3 and 4). The fault planes dip towards the northeast, and are indicative of the main direction of movement, with very rare examples dipping in the reverse direction. Thrust ramp folding has created a series of secondary antithetic, tensional faults (e.g. the Lungkarta structure, T82-57, Plate 1; Yowalga structure, 80-009, Plate 1).

Normal faults are the least common fault type. They generally have a low displacement, with throws being less than 100 milliseconds (approximately 150 m) and rarely exceeding 200 milliseconds (approximately 300 m). Most of the displacement offsets Supersequence 1 strata, although later reactivation has resulted in minor displacement of Supersequence 3 and 4 or younger horizons.

Within the Yowalga area, the dominant strike orientation of the faults is to the southeast (145°), and can be identified in seismic data from the Browne Formation to the Table Hill Volcanics horizon. The faults show minor vertical displacement, and can be detected on both seismic and aeromagnetic data. This set of faults has a broad azimuth range, and may be subdivided into modes around 145° and 115° (Fig. 11). A northerly striking fault set is also recognized at around 010° through both the Top Browne Formation and Table Hill Volcanics horizons.

Substantial differences are apparent between faults identified on seismic data and those identified on aeromagnetic data. As a comparative test, faulting of the Table Hill Volcanics was compared in seismic and aeromagnetic interpretations. The Table Hill Volcanics is a good seismic reflector that enables an accurate identification of faults on seismic data, and has enough magnetic response to be reliably mapped by high-resolution aeromagnetics. Figure 11a shows an azimuth rosette of all the digitized faults identified on seismic data by JNOC in their SPA (JNOC, 1997). It can be interpreted as being virtually unimodal to 140°, with a very minor mode to 005°. Figure 11b shows an azimuth rosette for all the digitized, interpreted aeromagnetic faults in the same area. This is clearly bimodal, with the dominant mode to 150° and a substantial secondary mode to 015°. The north-northeasterly fault system is clearly under-represented in the seismic interpretation. Similarly, Figure 11c is an azimuth rosette of all the seismically identified faults in the Top Browne Formation horizon. It is again essentially unimodal to 135°, with a smaller mode to 170°. Figure 11d shows the azimuth rosette for all the aeromagnetic faults in the same horizon, and is clearly bimodal. The southeasterly mode may be divided into a dominant mode to 140°, with a subsidiary mode to 115°. The northerly mode seen on the seismic section is absent.

An interesting result of this comparison of seismically and magnetically interpreted fault orientations is the common rotation between modes when using the two methods. This is a result of the different density of control points in the two methods. A seismic interpreter must rely on a model for fault orientation, especially for one-line intersections, whereas magnetic rosettes show a greater spread of the modes because with the closer control this method can recognize the curvature of the fault planes. Integrated interpretation utilizing the available seismic, gravity, and aeromagnetic data is considered a more reliable indicator of fault and fold trends than one method alone.

Salt movement

Mobilization of salt can take place when it is buried under a denser overburden with a thickness of only 0.5–1 km (Warren, 1989). The Browne Formation, which contains a substantial amount of salt, is more than 2000 m thick in the Yowalga area. Salt mobilization in the Yowalga area was not initiated until the Browne Formation was buried under as much as 3000 m of denser overburden consisting of the Hussar, Kanpa, and Steptoe Formations. With such a thick salt sequence and thick dense overburden, the gravity instability in the basin was very large by the end of the Steptoe Formation deposition. Salt mobilization was triggered in the Yowalga area by tectonism, probably during the Areyonga Movement. Due to the gravity instability (reactive state) of the basin, contractional structures formed during this event were rapidly modified by halokinetic uplift. The Hussar, Kanpa, and Steptoe Formations formed a strong, brittle overburden to these structures, and true diapirs only formed where this overburden was removed by uplift and erosion.

JNOC (1997) recognized that the Yowalga area could be divided onto a number of laterally persistent zones based on the behaviour of salt in the area. Closest to the Musgrave Complex is a zone identified by JNOC as the Salt-ruptured Zone, which is followed by the Thrusted Zone, with the Western Platform furthest from the Musgrave Complex (Fig. 12). However, JNOC made no effort to explain the significance of the zones or their genetic relationship and timing. A genetic model explaining their origin and controls is presented here.

The Salt-ruptured Zone is an area of tension where salt intrusively penetrated the overlying sedimentary strata along lines of weakness. A number of salt diapirs have long been recognized from surface mapping (Jackson, 1976), and a linear alignment (the Browne Diapir) has been identified. Subsequent seismic interpretation has found additional salt walls that continue beyond the small surface outcrops, and can be mapped for more than 100 km (JNOC, 1997; Durrant and Associates, 1998). The Thrusted Zone is a zone of compression where thin-skinned, low-angle thrust faults, lubricated by salt within the Browne Formation, have produced ramp anticlines

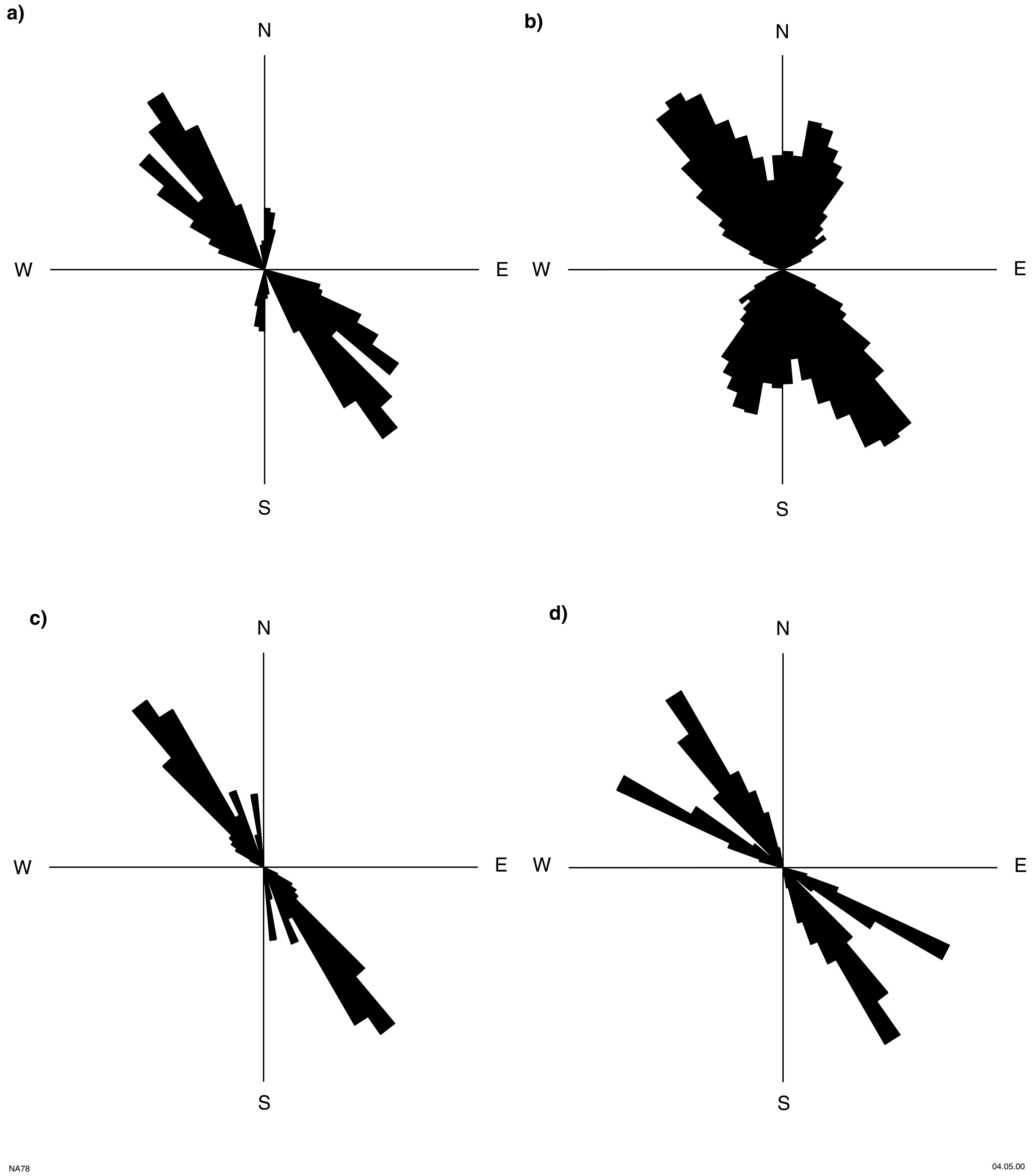


Figure 11. Azimuth rosettes for faults in the Yowalga area: a) seismic interpretations for faults at the top of the Table Hill Volcanics; b) aeromagnetic interpretations for faults at the top of the Table Hill Volcanics; c) seismic interpretations for faults at the Top Browne Formation; d) aeromagnetic interpretations for faults at the Top Browne Formation

(Plate 1, Lungkarta structure). Minor folding and the stacking of thrust sheets has generated thickened pods of the Browne Formation. The sense of thrusting is from the northeast to the southwest, and the thickened pods are oriented northwest–southeast. The Western Platform is a zone of stability, with an absence of salt intrusion or thrusting.

The driving force for these features is believed to be gravity or roof detachment of thrust faults within the Browne Formation. When uplift of the northern margin of the basin took place (post-Supersequence 1), either due to compression from the Musgrave Complex or relaxation after thrusting ceased, the sedimentary pile became unstable and began to glide southwest along the salt beds. This was probably as large cohesive sheets that created a zone of tension at their trailing edge, thus resulting in faults into which salt was injected, filling the space left by the moving block. At the other end of these gliding blocks, the leading edge encountered the stable opposite-dipping Western Platform, and the motion was taken up by the overthrusting of sheets of sedimentary rocks and

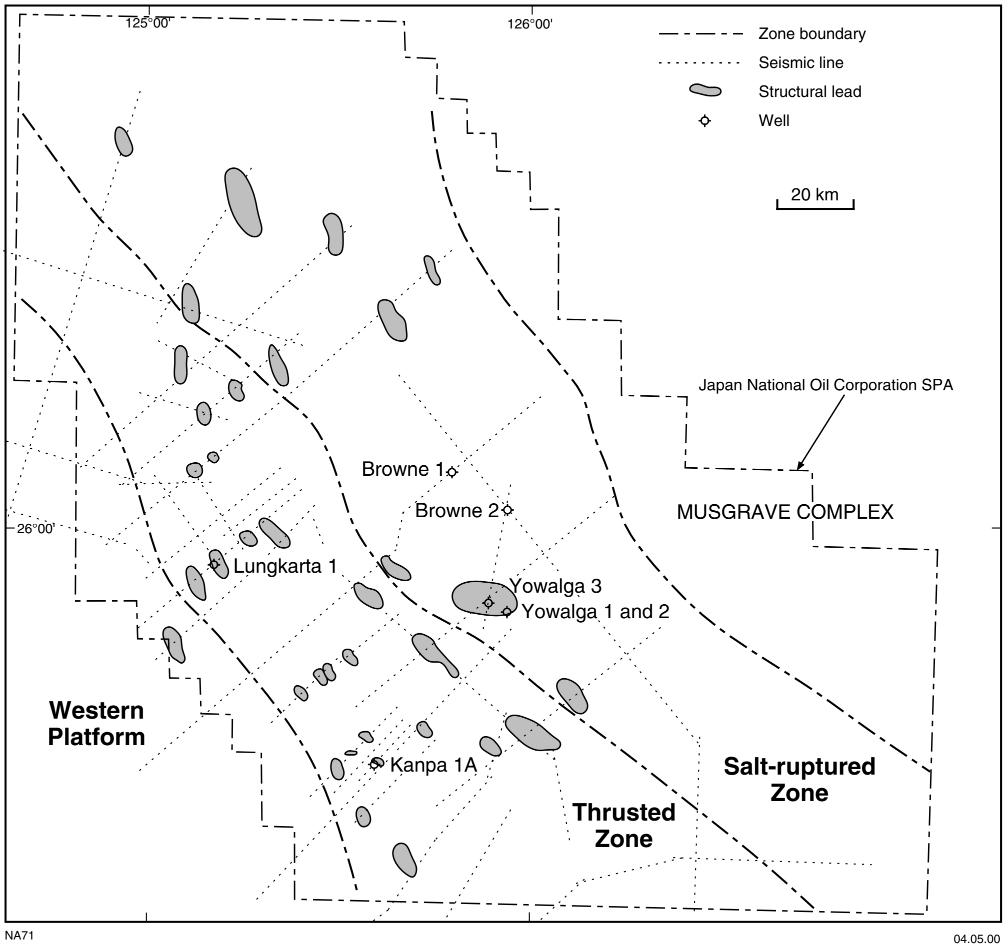


Figure 12. Distribution of structures and tectonic zoning in the Yowalga area

the resultant folding (Fig. 13). The relationship between the compressive and extensional fields is thus explained.

It is clear that movements involving more than a single sheet took place, and sub-sheets or completely independent sheets were likely. Although the salt wall can be mapped seismically as a single unit, it is more likely that movement took place in a number of fault-separated, semi-independent sheets. The intensity of thrusting was also highly variable, and more detailed mapping is required to arrive at a fully balanced reconstruction.

On seismic lines, the timing of the major salt movement (post-Steptoe Formation) can be seen to have taken place between the deposition of Supersequence 1 and the Supersequence 3 Lupton Formation (Plate 1). The Supersequence 1 strata above the Browne Formation salt are deformed and eroded. The overlying Lupton Formation rests on these with a marked angular unconformity in places, and shows no effect of the underlying deformation (Plate 1). Later movements of diapiric salt have penetrated this unconformity and deformed the younger strata, but this is clearly a later remobilization of the salt. There is evidence from displaced surface laterite that some diapirism may still be taking place.

A number of features described as ‘rim synclines’ have been identified on several seismic sections (WGC, 1997). These features were interpreted to indicate major folding during the Areyonga Movement, with erosion over the crests of the folds and syntectonic deposition in the ‘rim synclines’. The authors’ interpretation of the seismic data is that bedding in the synclines is parallel and does not thicken into the synclines, which are therefore not depositional depressions. The overlying unconformity separates Supersequence 1 and Supersequence 3 units, thus suggesting folding during an earlier major structural event such as the Areyonga Movement (Plate 1), with no syntectonic depositional units preserved along the synclinal axes. A regional angular unconformity separates the folded Supersequence 1 units from less folded Supersequence 3 or younger units. An additional section of the Lupton Formation (Supersequence 3) or McFadden Formation equivalent (Supersequence 4) is sometimes present adjacent to the salt intrusions, suggesting that there may have been additional salt movement, including salt withdrawal, at these later times.

Dolerite dykes

Mafic dykes were mapped from aeromagnetic data by WGC (1997) as a number of long, narrow, positive and negative magnetic trends. They have a general north-

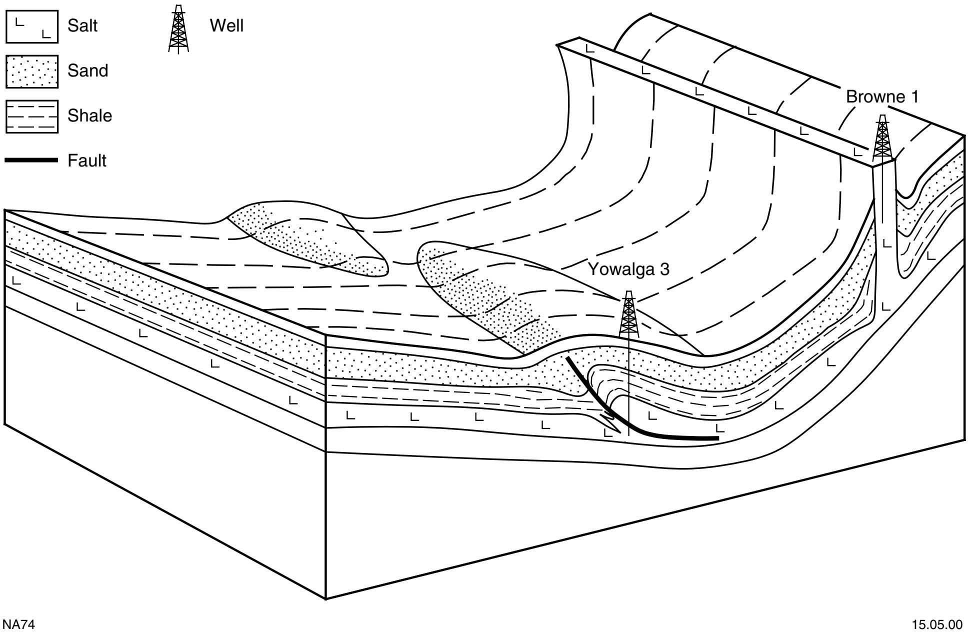


Figure 13. Schematic figure showing the relationship of salt walls and thrust sheets. Uplift results in a 'raft' of sediment gliding downslope on the salt, overthrusting at the leading edge, and a tension void at the trailing edge. Browne 1 tested an injection feature, and Yowalga 3 tested an anticline draped over a thrust complex

easterly azimuth of 040°, with mapped lengths in excess of 25 km. They are present either individually, or in swarms where they are as close as 2–3 km apart (Fig. 14). The preferred orientation of 040° is orthogonal to the major contractional fault systems. Dolerite dykes, such as the Amata and Gairdner dykes that have been mapped from outcrop and aeromagnetic data, have been dated at 800 Ma by Zhao et al. (1994). The dyke swarms extend from the Gawler Craton to the Musgrave Complex (Zhao et al. 1994, fig. 1). The continuity of dyke orientation over this distance possibly indicates some control by pre-existing basement structures formed during initial compression. Townson (1985), using a more extensive magnetic dataset from beyond the area reviewed by WGC (1997), reported another two sets of dykes; one approximately north–south oriented and the other with a northwesterly orientation. He found magnetic anomalies, which he interpreted as dykes, that were traceable for up to 140 km.

The dykes do not appear to have substantially affected the geothermal history of the adjacent sedimentary strata. WGC (1997) suggested that the dykes might form barriers to the migration of petroleum. However, their orientation is basically orthogonal to the main fold axes, and probably post-structural, so they have little impact on hydrocarbon prospectivity in the Yowalga area.

Folding

The majority of large-scale folds in the Yowalga area are either in halokinetic or ramp anticline folds (or both) associated with tectonic and gravity-driven thrust faults. Large-scale folds along the northern margin of the Yowalga area are reflected in outcrops of the Townsend Quartzite, with local dips approaching vertical (Stevens, M., 1999, pers. comm.).

Lungkarta 1 was drilled on a readily identifiable ramp anticline (Plate 1). Tensional faulting developed during this folding may be a porosity-productivity enhancement mechanism for carbonates, but also increases the risk of seal failure in such features. Such folds are aligned with the parent thrust fault, and have a northwesterly axial orientation.

Most of the mapped folds are associated with drape over deeper salt-enhanced features. Thus, most of these affect the upper parts of the Browne Formation, and the Hussar, Kanpa, and Steptoe Formations. Other folds formed in response to later halokinetic movements such as salt withdrawal and diapirism. Salt walls with a length of 140 km have been mapped (JNOC, 1997), and these may provide very large structural traps for hydrocarbons. As well as having great lateral extent, these salt walls create vertical relief of up to several hundred metres in the flanking horizons, thus creating large-volume potential traps. Post-Areyonga Movement erosion has removed most of the topography generated by these major folds, before deposition of the overlying sediments (e.g. Lupton Formation, Plate 1).

Smaller but more complicated ramp anticlines extend over a large area and also have high relief. Lengths range from 10 to 40 km, with widths of 5 to 10 km (Fig. 3). The major axes of these structures parallel the northwesterly orientation of the causative faults. The Hussar, Kanpa, and Steptoe Formations also provide reservoirs and seals in these structures.

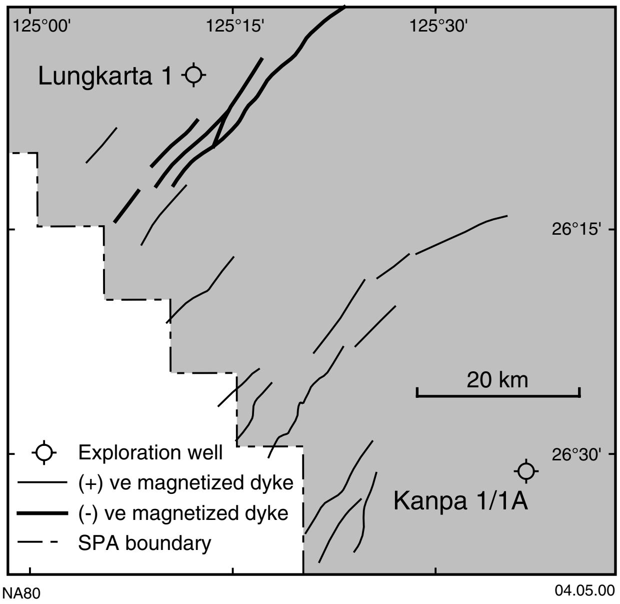


Figure 14. Interpreted magnetic linear dykes in the Yowalga area (after JNOC, 1997)

Basin evolution

The origin and development of the Officer Basin has been the subject of considerable analysis, and a number of basin-forming mechanisms have been presented. The simplest of these is the concept of a single Centralian Superbasin (Walter and Gorter, 1994) encompassing the Georgina, Ngalia, Officer, and Savory Basins. This region was believed to have maintained its singularity until thrusting and central uplift took place during the Petermann Ranges Orogeny. Basin sag was presumed to be due to crustal thinning over a large mantle plume. However, the mantle plume proposed would be located under the Adelaide Rift Complex (Zhao et al., 1994), and it is hard to reconcile the palaeoisopachs for Supersequence 1 strata presented by Walter and Gorter (1994, fig. 4) as being the result of a plume in such a position. Another point against such a thermal-sag mechanism is that the Officer Basin rests on crust with a measured thickness of 42 km (Lindsay and Leven, 1996), rather than a thinned crust. Finally, as pointed out by Lambeck (1984), both the magnitude and duration of the thermally induced subsidence do not fit with the Officer Basin's history. To produce a basin containing the thickness of Supersequence 1 sediments present in the Officer Basin would require very extensive erosion of the crust prior to cooling. If the subsequent deposition of Supersequence 2, 3, and 4 sediments are also attributed to such a cause, the timing of the thermal event is overly long.

Lambeck (1984) suggested a model for subsidence where compression of the crust magnified any inhomogeneity of the crustal loading. His model better reflects the Amadeus–Ngalia basin complex rather than the Officer Basin. The jostling of tectonic plates during the formation and disintegration of Rodinia (Myers et al., 1996) was very likely, and probably did cause such compressive phases. However, a single compression can not be invoked for the contemporaneous subsidence in the Georgina Basin and Adelaide Rift Complex.

Although Lambeck (1984) excluded a foreland-basin origin for the Officer Basin, this style of basin development is reflected in many of the aspects of sedimentation and structure observed in the Yowalga area. Unfortunately, critical data for the margin with the Musgrave Complex, which would be required to confirm such a model, are currently limited.

A point in favour of the Yowalga area having its northern margin adjacent to the Musgrave Complex is the fact that Daniels (1974) measured current-direction indicators in the fluvial to shallow-marine Townsend Quartzite near this contact and found that they suggested a provenance to the north. Thus the Centralian Superbasin could have had an emergent area in the region of the Musgrave Complex, even at the very beginning of Supersequence 1 deposition. Current-direction indicators at the Empress 1A location show currents were from the south. Following deposition of the sandy Townsend Quartzite, an adequate supply of sediment was not yet established and deep-water conditions developed, as shown by the turbidites of the Lefroy Formation in Empress 1A. Deep-water conditions continued until the basin was filled to near sea level, and shallow-water to sabkha deposition began. In general, the basin subsided smoothly, with sedimentation keeping pace with the creation of accommodation space, and the bulk of the sediments were deposited in shallow water. However, repeated periods of rapid creation of accommodation space are reflected in the thick shales present in Supersequence 1, and these are interpreted as representing intermittent loading of the foreland basin, which caused subsidence. The extensive thinner sediment packages may represent smaller loading events. Another indicator of an asymmetric foreland basin is the extreme lateral persistence of sedimentary packages that are seen on seismic data and gradually thicken to the north.

A single seismic line across the Musgrave Complex – Officer Basin contact has been acquired by AGSO, in South Australia near the South Australia – Western Australia border. It has been interpreted by Leven and Lindsay (1995, fig. 6) to show thrusting from the Musgrave Complex that has terminated at the top of the Supersequence 1 strata, with the lower Supersequence 1 strata faulted and missing. The movement was clearly during or after deposition of Supersequence 1, and could have provided the loading mechanism for basin subsidence. Leven and Lindsay (1995, fig. 5) provided additional evidence for the structure of Supersequence 1 by pointing out that Supersequence 1 sediments were deformed before Supersequence 2 deposition began. Leven and Lindsay (1995) stated that 'They represent a net shortening of the lower succession relative to the upper succession, and are interpreted to have formed by flowage within the Alinya Formation (an evaporitic unit) in response to the compression of the Officer Basin sediments during the southward thrusting of the Musgrave Block'. Though this seismic line is located far away from the Yowalga area, a similar thrusted margin, with concomitant loading, is postulated for the Yowalga area.

In general, based on the available data, a foreland style of basin appears to be the best model that can be applied to the Yowalga area during Supersequence 1 deposition. The following section is a re-interpretation of the basin evolution of the Yowalga area, based on the new structural and sequence-stratigraphic interpretations presented above.

What has previously been described as the Yowalga Sub-basin (Townson, 1985; Carlsen et al., 1999) is here referred to simply as the Yowalga area. Townson (1985) suggested a further subdivision of the Yowalga area into an axial ‘trough’ flanked to the south by a ‘hinge zone’, with a ‘platform area’ along the southern limit of the Neoproterozoic outcrops. In an effort to map out these zones, structural elements such as the Westwood Shelf were delineated from the potential-field data. Hocking (1994) defined the edge of the Westwood Shelf as the 3 km depth-to-magnetic basement contour, but there appears to be no depositional evidence for such a boundary. Available data only allow the definition of an erosional remnant of a larger basin, with no clear indication of a basin centre or northern, eastern, or western depositional limits. Current geophysical and well data indicate that the sedimentary sequence consistently thickens from a condensed section on the southwestern margin into a thick depocentre in the northeast. No northerly thinning has been proved that would be consistent with the long, shallow, north-dipping southern flank of the basin. Available seismic data suggest that the very uniform deposition of Supersequence 1 can be extrapolated beyond the seismic control, and beyond what was previously defined from potential-fields data as the limits of the Yowalga Sub-basin. For example, on seismic profiles there is no evidence of the Neal Arch (Hocking, 1994). The authors interpret the Neal Arch to be a potential-field response to changes in the composition of the basement. The Yowalga area is best regarded as a remnant of a far larger basin that was of very low relief and had its main depocentre to the north.

Supersequence 1

The initiation of the Officer Basin is the most difficult aspect to determine, as its base is difficult to identify on seismic data, it is infrequently penetrated by drillholes, and the basement changes character rapidly, thus making potential-field analysis unreliable. The sedimentary fill of the Neoproterozoic strata began on a previously deformed irregular basement surface of the Musgrave Complex. There is very little control on the lower part of the stratigraphic section (Townsend Quartzite and Lefroy Formation), and interpretations in the past have been influenced by analogy with other basins with no local control. Field observations of sedimentary transport directions for the Townsend Quartzite, Dean Quartzite, Heavitree Quartzite, and Pindyin Sandstone are extremely limited. Daniels (1974) showed that the Townsend Quartzite along the southern margin of the Musgrave Complex had a source to the north and northeast, and he reported conformable to unconformable contacts with the underlying igneous and metamorphic units. He measured current-direction indicators in the fluvial to shallow-marine Townsend Quartzite near these contacts, and the results suggested a provenance to the north.

Forman (1966) and Wells et al. (1970) reported that the Dean Quartzite rests conformably to unconformably on the Dixon Range and Bloods Range beds, and includes small subangular fragments of the amygdaloidal basalt and vein quartz of the Mount Harris Basalt. Basal conglomerates were deposited as valley fills on the uneven surface of the unconformity. The main body of the thick orthoquartzite probably represents sand transported from the strandline of a platform or stable shelf environment into a deeper water environment (Forman, 1972).

Daniels (1970) reported cross-bedding orientations that indicated currents from both the east and west; however, no conclusions were given. These observations do not support the theory that early sedimentation in the Centralian Superbasin was onto a mature peneplain topography. Thus the Centralian Superbasin appears to have contained an emergent area in the region of the Musgrave Complex, at the onset of Supersequence 1 deposition.

Lindsay (1999) presented an unquantified number of palaeocurrent observations for the Heavitree Quartzite, from exposures near the northeastern margin of the Amadeus Basin. His observations indicate a major transport direction from southeast to northwest (unimodal flow), and secondary transport directions from the northeast and southwest (bimodal flow). These observations do not support the conclusion that the basal sandstones and conglomerates of the Centralian Superbasin are all derived from the basin edge and have been transported into the basin. Only a single well has intersected the Heavitree Quartzite in the Amadeus Basin. Magee 1 (Wakelin-King, 1994) penetrated a 4.6 m-thick interval of the Heavitree Quartzite over a local basement high. This well has shown that the basal clastic units of the Centralian Superbasin are not uniformly distributed as numerous authors have suggested.

The Pindyin Sandstone of the South Australian Officer Basin only outcrops along the southern margin of the Musgrave Complex (Major, 1973). Only one petroleum exploration well, Giles 1, intersects the unit. In outcrop, the sandstone is approximately 200 m thick. In Giles 1, only 39 m of the unit were penetrated, but seismic data suggest that the thickness ranges from 100 to 200 m (Morton and Drexel, 1997). Palaeocurrent interpretation of cross-beds, the southward thinning of the conglomerate, and the orientation of ripple marks imply a northern provenance for the Pindyin Sandstone (Morton and Drexel, 1997).

Current-direction indicators at the Empress 1A location show that currents were from the south (Stevens and Apak, 1999). This Report provides new interpretations on the significance of contacts between basement, the Townsend Quartzite – Lefroy Formation depositional unit, and the Browne Formation. Our data demonstrate that the Yowalga area formed part of an asymmetrical basin, with the main depositional axis close to the Musgrave Complex, and with point sources of coarse clastic material along the northeastern margin. No syndepositional extensional faults are indicated in core, well-log, or seismic data. Poor subsalt reflectors in areas of thick Supersequence 1 strata are interpreted to indicate that no half-graben or other extensional structures underlie these features. The southwest hinge margin of the depocentre may have been the location of a peripheral bulge during early sedimentation, as the Townsend Quartzite – Lefroy Formation depositional unit thins from approximately 800 m along the Musgrave Complex to less than 50 m in Empress 1A. In general, the basin subsided smoothly, with sedimentation keeping pace with accommodation space creation, and the bulk of the sediments were deposited in shallow water. However, repeated periods of rapid accommodation space creation are reflected in the thick shales present in the section, and these are interpreted to represent intermittent loading of the foreland basin, thus causing subsidence.

Recent coring at Vines 1, on the northern margin of the Waigen Sub-basin and adjacent to the Musgrave Complex, revealed at least a 400 m-thick interval of allochthonous sediments of probable Supersequence 1 strata (Apak et al., in prep.). Geophysical modelling following drilling of this well indicates the proximity of large-scale thrust faults originating in the basement under the Musgrave Complex. These faults were responsible for the tectonic instability of this region at the time of deposition of these strata. The extensive thinner strata packages may represent smaller loading events. No overall decrease in subsidence rates would be expected if the basin was subsiding in response to stabilization following termination of a thermal event related to a mantle plume.

The Browne Formation has some well control, but is complicated by mobile salt content that has resulted in rapid changes in thickness and structural complexity, thus making seismic interpretation difficult. The remaining Supersequence 1 units are easily traced on seismic data and can be confidently correlated between wells, so that basin architecture and evolution can be reliably modelled for this time frame. A desirable outcome of any study of this nature is the correct identification of the orogenic movements responsible for initiating the various cycles of deposition and erosion. In the study area, seismic data indicate that the Areyonga Movement was the most significant tectonic event, whereas the subsequent movements resulted in smaller depocentres with less sediment fill and structural complexity.

The basement reflector is generally of very poor quality and lateral continuity, thus resulting in uncertainty in mapping this horizon. The Townsend Quartzite – Lefroy Formation succession has been mapped seismically as a single package, as no reflector is present at the interface. This supports the interpretation of these units as lateral facies variations of a single depositional unit. The Base Browne Formation, seismically correlated from Kanpa 1A to the rest of the Yowalga area, has a low-amplitude reflection and poor lateral continuity. As already discussed under **Sequence stratigraphy**, it is more likely that the Base Browne Formation contact is dominantly with the Lefroy Formation facies rather than the Townsend Quartzite, thus the resulting low-amplitude reflection between units of similar seismic impedance.

The overlying Browne Formation is better understood than the older strata. This knowledge is derived from a number of well intersections, although only Kanpa 1A and Empress 1A have penetrated the entire unit, and also from better quality seismic reflectors. The presence of salt has resulted in structural complexity through diapiric injection and salt-lubricated faulting, which commonly make seismic interpretation difficult. The mobility of the salt has resulted in dramatic variations in the thickness of the unit. It should be noted that there is difficulty in explaining these volume changes by salt movement alone, as even the greatest thickness of salt penetrated (343 m in Kanpa 1A) would be insufficient to explain all the thickness variations present.

Based on well intersections, the Browne Formation is thinnest in Empress 1A, where it is 275 m thick, and is 1152 m thick in Kanpa 1A, whereas an incomplete section in Yowalga 3 has a total thickness of 2316 m. This variation is due to a combination of two factors; thickness variations of individual units and the presence of additional units. The area around Yowalga 3 must have been in a more active part of the basin where the two oldest parasequence sets were deposited (see **Sequence stratigraphy**). The fact that the basal section of B2 also has a restricted distribution shows that the basin was still subsiding irregularly during B2 deposition. The remaining parasequence sets only show a gradual thickening of the individual units in the Yowalga 3 area. Based on the isochron map (Fig. 15), the Browne Formation is thickest along a northwesterly trend adjacent to, and parallel with, the Musgrave Complex.

The more persistent deeper water setting of Yowalga 3, with respect to the other wells, is also reflected in the lithologies present in the wells. In Yowalga 3, dolomite is the dominant lithology (53%), thus indicating more normal marine conditions, whereas in Kanpa 1A dolomite is 26% of the lithology and in Empress 1A it is 18%, which suggests that they reflect more emergent environments with less preservation potential. Mudstone has a negative correlation with dolomite, representing 36% of the section in Yowalga 3, 44% in Kanpa 1A, and 51% in Empress 1A. The presence of salt has a positive correlation with the mudstone content. Salt represents only 11% of the lithology in Yowalga 3, but 30% in Kanpa 1A, and 31% in Empress 1A. This can be explained as being the result of a progressively emergent evaporite to sabkha depositional environment.

Sandstone is not abundant, and is only present as thin isolated beds. Though clearly controlled by supply, its general absence probably reflects the energy regime of this very low relief basin. Establishment of the continuity of these depositional units, and the ability to predict their lateral variations, has implications for the prediction of the distribution of reservoirs, seals, and source rocks throughout the basin.

From log correlation, six parasequence sets have been identified as forming part of the Browne Formation. Not all are represented in Empress 1A, but the facies mosaic

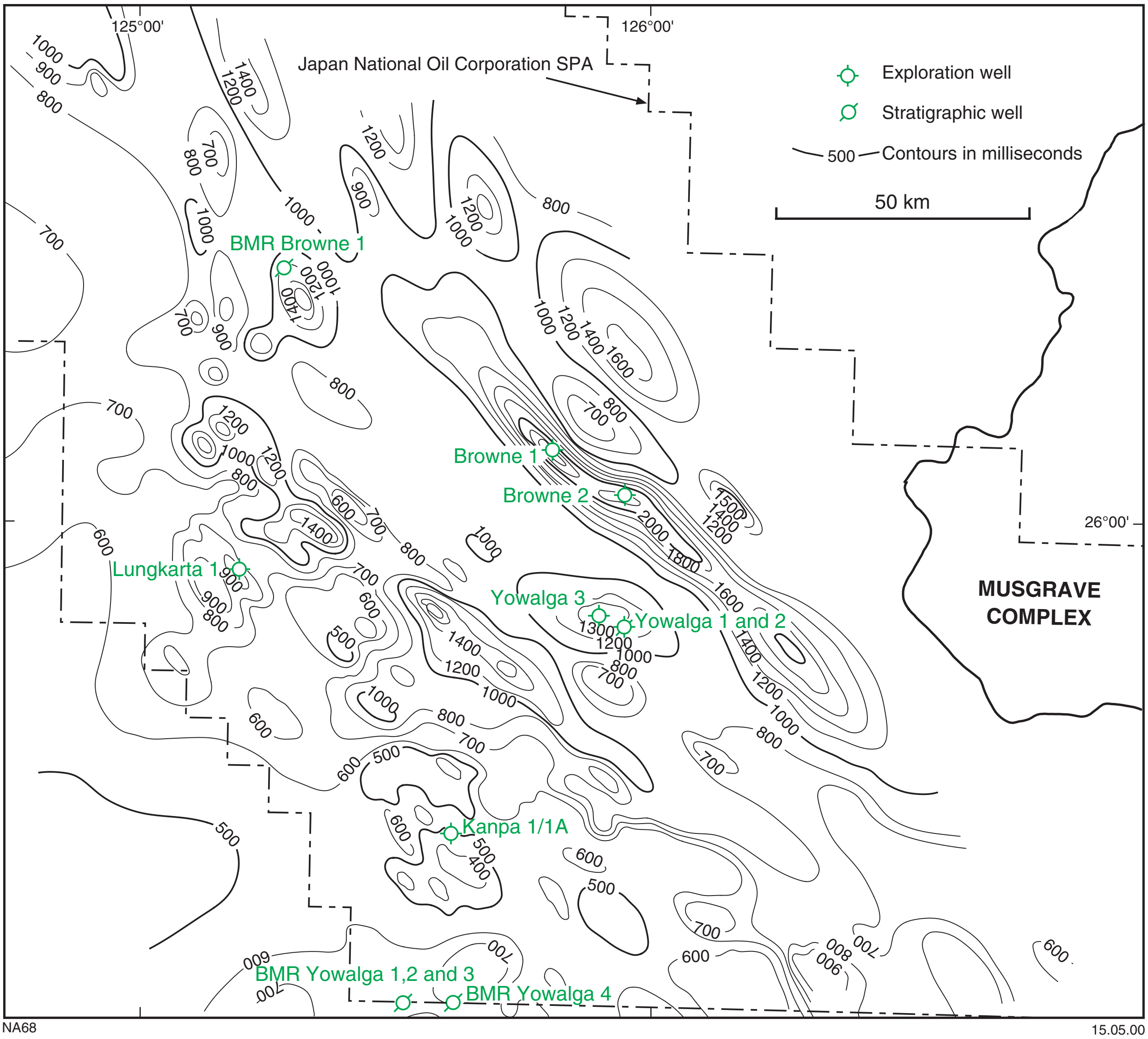


Figure 15. Browne Formation isochron map (after JNOC, 1997)

recognized in this completely cored well is believed to be representative of those generally present in the formation.

After deposition of the Browne Formation, the basin expanded laterally to its full size, with deposition filling in all the irregularities. Deposition in the Yowalga area continued under similar tectonically quiet conditions during deposition of the Hussar Formation. The overall configuration was of a shallow, low-relief depression. A major marine transgression took place at the base of the Hussar Formation, and a thick section of argillaceous rocks was deposited across the Yowalga area. There is very little change in thickness in these rocks from Yowalga 3 to Empress 1A. As the sea flooded the basin, it cut off the sediment source, and shallow, clear-water conditions began in the centre of the basin, with the deposition of extensive shallow-water carbonates. H2, comprising shale and dolomite only 20–40 m thick, can be traced from Yowalga 3 to Empress 1A, thus showing how flat the basin must have been and how quickly these units would have prograded across it.

The third cycle of deposition (H3) also consisted predominantly of shale and thin carbonate units. On the other hand, the remaining two parasequence sets are characterized by a high sandstone content, which indicates that a sand source had become available, thus resulting in two repeated prograding shoreface successions (Fig. 8).

The three lowest parasequence sets have a relatively constant thickness in all three wells, with only minor thinning between Yowalga 3 and Empress 1A. However, the upper two parasequence sets show much more rapid thickening towards the Yowalga 3 area, indicating that the basin had again begun to subside irregularly. This tectonic activity may have provided the source of the sand that is characteristic of deposits of this age. As can be seen from the isochron map for the Hussar Formation (Fig. 16), the

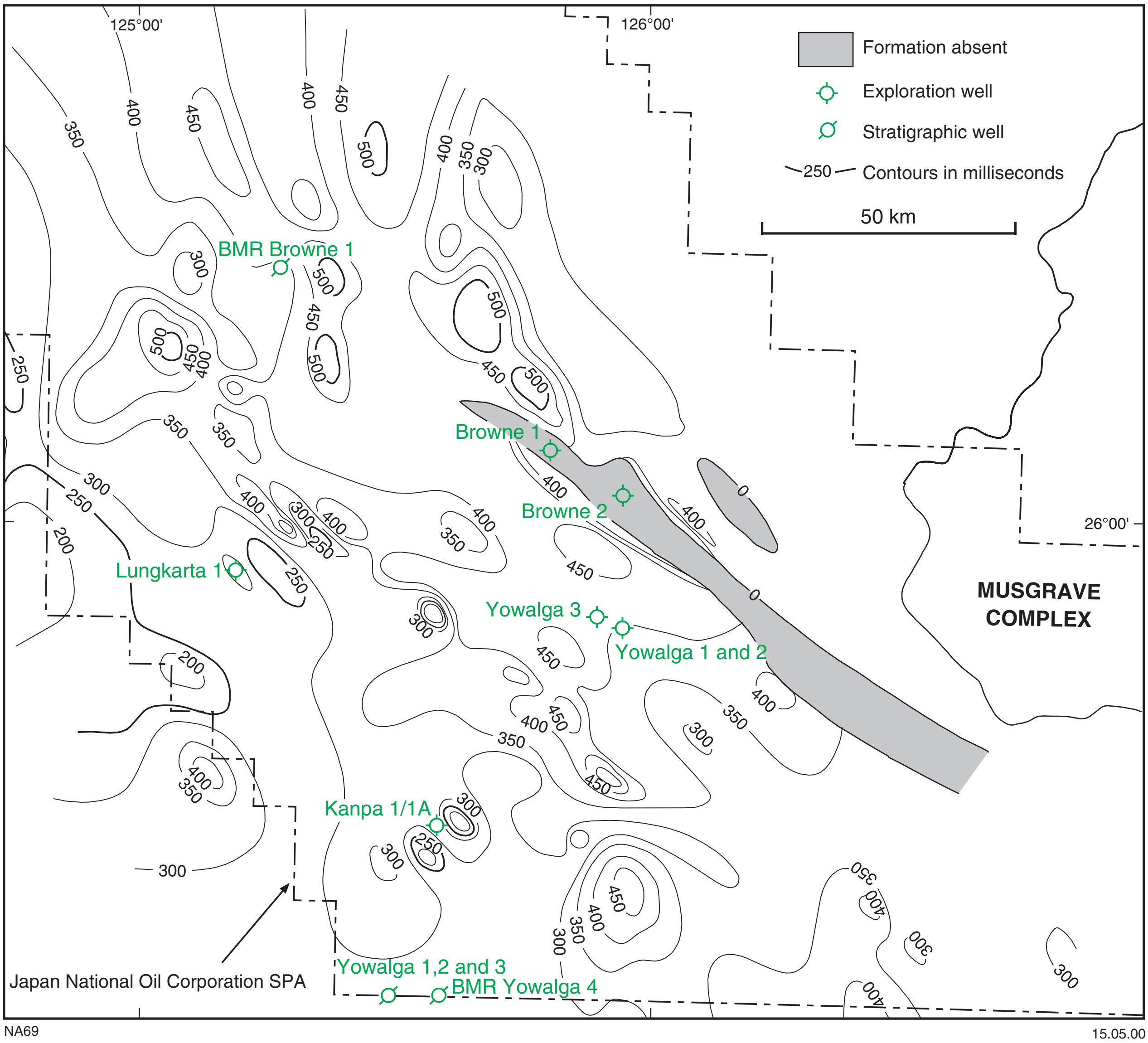


Figure 16. Hussar Formation isochron map (after JNOC, 1997)

area around Yowalga 3 was one of relatively thicker deposition. Apart from this region, the Hussar Formation exhibits a relatively uniform thickness, gradually thinning towards the basin margin in the southwest.

Following deposition of Sequence H (modified Hussar Formation) and its correlative parasequences, a substantial transgression again deposited another thick basal claystone. The fact that the basin was still subsiding is shown by the pronounced thickening of the basal succession from Empress 1A to Kanpa 1A; the rate of deposition of the Kanpa Formation being higher than that of the underlying Hussar Formation successions. The upper parasequence (K2) shows a more constant thickness, and the dominance by carbonates indicates a cutting off of siliciclastic sources (Fig. 9). The Kanpa Formation exhibits a similar thickness and areal distribution to the Hussar Formation. This younger formation has been subjected to even more erosion than the Hussar Formation at the Yowalga 3 and Lungkarta 1 locations. For these reasons, the isochron map of the Kanpa Formation (Fig. 17) reflects mainly preserved thicknesses of the formation, rather than the initial depositional thickness. Seismic data, nevertheless, clearly show the lateral persistence of the units, which is similar to that seen in the underlying formations, thus suggesting a similar extent to the basin as that indicated by the underlying formations.

Based on only two control points, the authors' interpretation is that the basin initially deepened and contracted in size. This implies a difference in elevation in excess of 250 m between the Kanpa 1A and Empress 1A locations, and a differential subsidence of the same magnitude in the basin.

The Steptoe Formation in Kanpa 1A and Empress 1 and 1A is the youngest portion of Super-sequence 1 intersected by the wells. Based on seismic data,

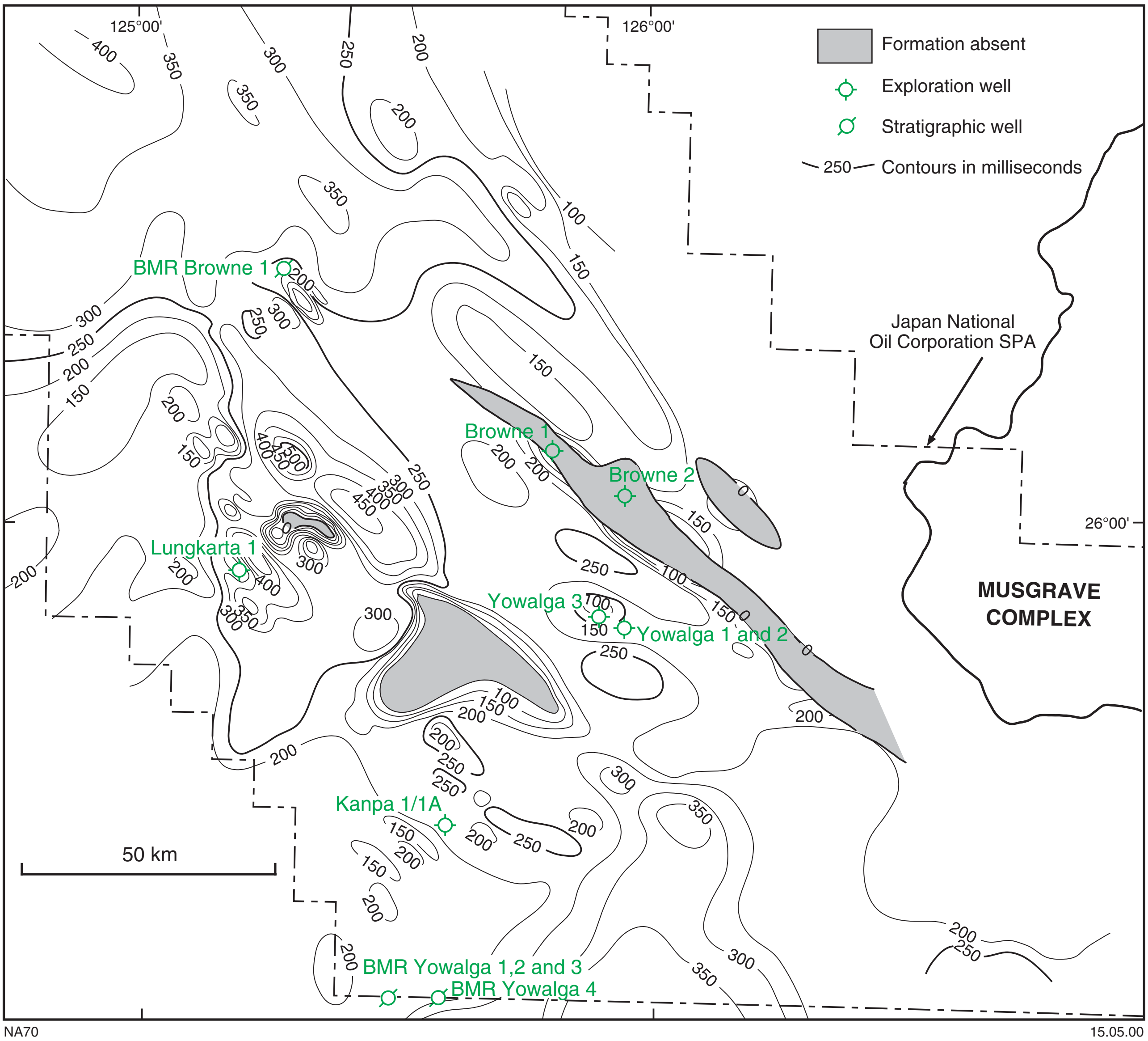


Figure 17. Kanpa Formation isochron map (after JNOC, 1997)

it can be argued that deposition of this sequence continued longer than that indicated by the eroded fragments preserved in the wells, before basin instability resulted in a phase of halokinetic faulting and folding that ended deposition and created elevated areas that were then subject to erosion for a long period. The Steptoe and Kanpa Formations have been severely eroded. The northerly trending Westwood Fault and the northeasterly oriented fault to the west (Fig. 10) were active during the Areyonga Movement and Petermann Ranges Orogeny, as shown by erosion of the upper part of the Supersequence 1 strata (Fig. 17). The areas along these fault trends became uplifted, and were severely eroded during the Areyonga Movement and Petermann Ranges Orogeny.

In general, in the Yowalga area, Yowalga 3 is interpreted as the deepest (medial) control within the basin, and Kanpa 1A and Lungkarta 1 are located closer to the stable platform, whereas Empress 1A is the closest control to the platform and western margin. This western margin may represent a peripheral bulge at the onset of deposition in the main depocentre. Sediment thickness, the facies, and the abundance of erosional hiatuses at these locations suggest this to be the case. The proximal northern portion of the basin received the coarsest material, which was shed as deltaic sediments off the Musgrave Complex. Initial downwarping is interpreted to have resulted from crustal flexure following compressional uplift and crustal thickening of the Musgrave Complex. This was then enhanced by depositional loading, both by allochthonous material derived from the Musgrave Complex, and by autochthonous carbonates and evaporites that form a significant proportion of the section. Sedimentation largely kept pace with the creation of accommodation space, so that the water depth was always shallow. The greatest water depth was probably present during deposition of the Lefroy Formation, during a period of relative sediment starvation. Phases of increased subsidence, indicated by thick shale intervals, may represent eustatic changes, but more likely reflect climaxing phases in loading of the Musgrave Complex. Thinner successions represent transgressive systems tracts during periods of decreased subsidence rates.

End of Supersequence 1 (Areyonga Movement)

Following deposition of the Steptoe Formation, a strong structural phase associated with a pronounced tectonic event, the Areyonga Movement (new interpretation), resulted in rejuvenation of the older basement structures. The Areyonga Movement occurred in central Australia as Rodinia began to breakup and Laurentia separated from Gondwana (Baillie et al., 1994). Separation took place near the Adelaide Rift Complex and this eastern area continued to subside, whereas the distant Officer Basin in the west probably continued as a high during the Sturtian. Supersequence 1 strata were folded and faulted, and significant amounts of erosion took place, particularly over salt-emplacement features and in basin-margin areas. It is difficult to predict the amount of erosion in these areas, although at least 1000 m of strata have been removed, as can be proved by the simple correlation of the section between Yowalga 3 and Kanpa 1A. Seismic sections show much greater erosion than this in some places (Plate 1). The duration of the lacuna is uncertain, and it may also have included uplift due to the Souths Range Movement. The Sturtian Supersequence 2 sedimentation is not represented in the western Officer Basin. The absence of Supersequence 2 may be either due to non-deposition or later erosion, and is interpreted to be related to the causes of the Areyonga Movement. Subsidence recommenced during deposition of Supersequences 3 and 4, but it was very mild, as shown by the limited thicknesses of these younger deposits.

Supersequence 3

After the Areyonga Movement, gentle subsidence took place, with the establishment of glacigene conditions early in the Marinoan, and the deposition of the glacigene Lupton Formation (Grey et al., 1999). Although tillites have been described within the unit (Jackson and van de Graaff, 1981), these are now interpreted to be poorly sorted mass flows in a submarine fan (Carlsen et al., 1999). Although striated and faceted pebbles are present, they are regarded as more representative of the provenance than the environment of deposition. The massive sandstone, cross-bedded sandstone, minor laminated sandstone, and diamictite are all interpreted as mass-flow – turbidite deposits. The basin was not deep, and the amount of sedimentation was in the order of only 200–300 m, although no complete, uneroded section has been measured. Minor salt-withdrawal rim synclines of this age are suggested on seismic data, indicating a rejuvenation of salt diapirism.

End of Supersequence 3 (Petermann Ranges Orogeny)

As Gondwana began to further assemble, central Australia experienced phases of transpression and the reinitiation of basin subsidence, with deposition of Marinoan strata. The culmination of this phase was the Petermann Ranges Orogeny, as trans-Australian shear took place during the collision of the East Gondwana and African continental blocks (Baillie et al., 1994).

The Petermann Ranges Orogeny was a major period of tectonism in the Musgrave Complex and southern margin of the Amadeus Basin, but in the Yowalga area the effect was only minor. Uplift or base-level change resulted in partial erosion of the Lupton Formation.

Supersequence 4

After the Petermann Ranges Orogeny, subsidence again took place, resulting in deposition of the McFadden Formation equivalent. The gentle depression of the Officer Basin filled with the siliciclastic McFadden Formation equivalent. On seismic data, the strata can be seen to be unconformably filling the basin lows, and onlapping on and over the structural highs. Indications of rim synclines at this time suggest a further phase of salt mobilization. The McFadden Formation equivalent is a siliciclastic sequence that varies from being sand-dominated to shale-dominated in different parts of the basin. Shell Company of Australia (Townson, 1985) has seismically estimated a maximum thickness of 1200 m in the Lennis area, although well intersections are much less (172 m in Kanpa 1A). Renewed global continental breakup then resulted in further uplift and erosion that was followed by the extrusion of vast quantities of flood basalts over most of the depressions on the Australian plate. In the Officer Basin, these basalts have been identified as the Table Hill Volcanics, and represent the termination of the Officer Basin sedimentation. The base of this unit is used to define the Gunbarrel Basin.

The Delamerian Orogeny completed the Officer Basin deposition, and erosion again took place as the earlier tectonic highs were once again rejuvenated.

Post-Officer Basin development

Thin, extensive flows of tholeitic basalt of the Table Hill Volcanics heralded the beginning of the Gunbarrel Basin depositional cycle. The number of flows varies, but the maximum thickness encountered in wells is only 118 m in Yowalga 2. This subaerial unit was the last deposit on what must have been a largely emergent area for approximately 80 million years. After the Rodingan Movement, the shallow-marine Lennis Sandstone was deposited across the basin. Lithologies range from shale to sandstone, with occasional matrix-supported conglomerates (Jackson and van de Graaff, 1981; Stevens and Apak, 1999). The Alice Springs Orogeny then terminated the Gunbarrel Basin depositional cycle.

When deposition recommenced in the Carboniferous (Stevens and Apak, 1999), the Paterson Formation encroached from the Canning Basin and covered much of the underlying basins with a thin veneer of sediment. From the Permian to the Cretaceous, the region was emergent until the next major sea-level highstand transgressed this low-relief area and deposited the argillaceous Samuel Formation. Since the Cretaceous, the flat, subdued relief has been maintained, with periodic phases of river flow and erosion during wet periods that have been followed by pediplanation and wind deflation during arid periods (Jackson and van de Graaff, 1981). A thin, superficial blanket of sandstone and claystone has accumulated, which overlies a deep weathering profile within the underlying sediments.

Petroleum potential

Previous drilling

A total of seven petroleum wells has been drilled in the Yowalga area. The Hunt Oil group drilled Browne 1, Yowalga 1, and Browne 2 back-to-back in late 1965, and Yowalga 2 in early 1966. Shell Company of Australia drilled Yowalga 3 in 1980–81, and Kanpa 1A and Lungkarta 1 were drilled back-to-back in 1983–84. Another key well was the fully cored Empress 1 and 1A, which was drilled by GSWA in 1997.

In the first phase, drilling sites were poorly located, being based on surface expression, potential-field anomalies, and limited, isolated seismic data. Browne 1 and 2 were drilled by Hunt Oil Company on the basis of a closure mapped on a surface diapir, and limited seismic coverage. Both penetrated thin Cretaceous and Permian sediments before intersecting a residual cap rock over the intrusive Browne Formation. Shows were encountered in the cap rock, with gas-cut mud, cut fluorescence, and traces of oil recorded within sedimentary units in the gypsum in both wells. As migration access to these ‘reservoirs’ would be difficult through the encasing gypsum, and the structural validity at the locations is doubtful, even these small shows were encouraging.

Yowalga 1 and 2 were drilled after a Thumper six-fold seismic survey was conducted over gravity anomalies. This provided enough control to locate Yowalga 1. This well only reached the Lennis Sandstone, so Yowalga 2 was drilled, and penetrated through the Table Hill Volcanics to the Kanpa Formation. Because of the poor seismic control it is impossible to be certain of the structural validity of the Yowalga 2 location, even though the Table Hill Volcanics was picked on these early seismic lines. There is probably no closure within the penetrated section and no shows were encountered. Yowalga 2 resulted in the identification of the important seismic reflector associated with the Table Hill Volcanics.

In the second drilling phase, Shell Company of Australia applied for three exploration permits, and integrated the earlier results with a better regional understanding of the basin gained from GSWA and BMR mapping. The availability of Landsat, the reprocessing of the open-file and new potential-field data, and, most importantly, seismic detailing of anomalies allowed Shell Company of Australia to test three structures. Yowalga 3 was drilled on a complex rollover associated with thrusting. According to the company’s mapping, closure exists below the depths tested by Yowalga 2. Yowalga 3 is the deepest well in the Officer Basin and has a total depth (TD) of 4196.5 m. It penetrated most of the Officer Basin stratigraphic units, but did not reach basement. No shows were encountered in the well, and post-drilling evaluation of the structure by Shell Company of Australia showed it to be extremely faulted, making it doubtful that it is a valid trap. Their next well, Kanpa 1A, is also a key well. It penetrated the sequence to a sandy unit correlated with the Townsend Quartzite, and therefore almost reached basement. Brown oil staining, fluorescence, and cut fluorescence were recorded in the Steptoe Formation, within a sandstone bed overlain by a tight dolomite. The structure is again associated with a thrust, but appears to be simpler than the Yowalga structure and, based on the seismic data, the location is close to the culmination of the lower horizons. It is probably a valid structural test with some attic potential. Lungkarta 1 reached a TD of 1770 m, penetrating only to the Hussar Formation. No hydrocarbon shows, other than minor background levels of methane, were encountered. Again, the structure has been formed by arching over a thrust, and appears to be a simple anticline with the well location downflank, but seismic control is limited. The lack of success of this drilling campaign led Shell Company of Australia to relinquish their permits.

The most recent drilling in the Yowalga area was GSWA Empress 1 and 1A, which was cored from 105 m to a TD of 1624.6 m. This well is crucial to the unravelling of the sedimentology of the Officer Basin. Previous wells only provided electric logs and cuttings of the formations intersected, and there was very limited coring. This information enabled the definition of formations, and provided some control on the lithologies present, but the continuous core of Empress 1 and 1A has allowed the recognition of facies and their detailed spatial arrangement. The distribution of salt and other evaporites and source rocks has also been determined. It has been possible to reconstruct environments of deposition, and therefore basin architecture and development, throughout the entire penetrated section.

Petroleum generation

Information on petroleum generation requires an understanding of the quality, quantity, and distribution of potential source rocks within a sedimentary section, as well as the burial and thermal history of the section. This information for the Officer Basin has already been reported by Perincek (1998) and Ghori (1998a,b). JNOC (1997) conducted substantial additional geochemical analyses on Officer Basin wells and comparative wells in the Amadeus Basin. JNOC’s analyses included equivalent vitrinite reflectance, total organic carbon (TOC) and Rock-Eval, and this information and additional GSWA results are now available (Ghori, 1998b). These analyses have resulted in a new evaluation by GSWA, using the entire database in order to obtain more reliable interpretations on source-rock quality and quantity (Appendix). This interpretation of the data suggests that good quality, oil-prone source rocks exist throughout Supersequence 1 strata. New maturation modelling was also undertaken for the Yowalga area in recognition that previous modelling suffered from a poor understanding of the age of the sediments and the magnitude and duration of the erosive and unloading phases. The ages of the deposition and erosion phases are presented in the Appendix. The full maturation modelling is presented in the Appendix, and is discussed briefly below.

Source-rock type

The principal source of organic material, at the time of deposition of the Officer Basin sediments, was restricted to cyanobacteria and less abundant planktonic acritarchs. Due to their reliance on photosynthesis, most of the organic material was produced in relatively shallow-water or periodically emergent conditions. Gelatinous cyanobacterial mats were common, as illustrated by the abundance of stromatolites in the Empress 1A core. The low latitude of the basin at this time (Baillie et al., 1994) was a favourable location for high rates of organic productivity and associated high-preservation potential (Macqueen and Leckie, 1992). A detailed description of the source-rock facies, including production, transportation, and the preservation of organic material, is presented in Carlsen et al., 1999. Only a few additional comments are made here.

As the specific gravity of kerogen is very close to that of water, it is generally assumed that kerogen will be deposited with the finest sediment in quiet water. Most source-rock models assume that quiet water is the deep water towards the basin depocentre; however, any low-energy area can be effective in trapping organically enriched sediments. During the examination of the Empress 1A core, most of the sediments have been categorized as shallow-water deposits. However, any location behind an energy barrier can trap kerogen. An energy barrier may be emergent as in a beach–lagoon or dune–pond pairing, or submergent as in a submarine barrier bar. Other energy absorbers are wide shallow-water flats.

The main deterrent to the accumulation of source rocks in shallow water is the generally oxidizing nature of such environments, and again examination of the Empress 1 and 1A core confirms this characteristic of the sediments. They are typically red or grey in colour, and pyrite is uncommon. However, the stable character of the Yowalga area, and the resulting deposition of thin continuous successions, is very similar to the North Arabian Shelf, where Beydoun et al. (1992) have pointed out that 'the scale of the shelf prevented efficient water agitation and flushing from the ocean, so that even the shallow basins repeatedly became stratified and anoxic, except for their well-lit organically productive surface waters'. The same conditions would be expected in the Officer Basin. A number of other processes may also act to enrich the sediment in kerogen. In frequently hypersaline water, density stratification can take place, resulting in at least temporary reducing conditions. Salinity changes can also result in mass blooms or mortalities, which can greatly enrich horizons in organic material. High organic productivity may create a surplus of organic matter, thus reducing or depleting the supply of oxygen and resulting in locally reducing conditions. Such areas may also be associated with the growth of cyanobacterial mats. If this organic matter is rapidly covered by impermeable material, such as clay or evaporites, it may then be preserved.

All of the source-rock intervals so far identified have been in thin beds. This thin-bedded nature of the source rock has made its detection and quantification in ditch cuttings imprecise. Each source-rock bed is diluted by non-source material in the composite ditch-cuttings sample, thus resulting in an apparently lower quality on analysis. On the assumption that dilution or contamination results in lower analytical values, by selecting from our enlarged database only those samples with elevated values we have been able to characterize the actual source rock as containing type II kerogen (Appendix). This is what would theoretically be expected from a marine deposit of this age. The spread of values towards type III kerogen is due to oxidation and degradation depleting some of the hydrogen of the original biological contribution. Pyrolysis of the samples indicates a light-oil product with a substantial aromatics component, reflecting the type III tendency of the kerogen. A gas product is also probable (Appendix).

JNOC (1997), using a sophisticated geochemical program, indicated that the measured source-rock quality is somewhat pessimistic. Their computer package can identify the actual source-rock potential of material that has already passed some way through the oil window. For some of their modelling, the program suggested that the initial source-rock potential was in fact up to 2.5 times greater than the potential as analysed. From the Appendix it can be seen that most of the drilled section is not overmature, so that the present-day potential is generally close to the original potential.

Strata of source-rock quality have been found in most formations of Supersequence 1. They have been identified by Rock-Eval analysis in the Browne Formation in Kanpa 1A and Yowalga 3, in the Hussar Formation in Empress 1A and Yowalga 3, in the Kanpa Formation in Empress 1A, and in the Steptoe Formation in Empress 1 and 1A and Kanpa 1A. Using our newly identified sequence-stratigraphic subdivision as a correlation tool, these proved source intervals may now be correlated to the other wells in the Yowalga area (Ghori, 1998a, figs 5– 7) that usually at least show enrichment in their equivalent beds. Bearing in mind the limitations of using cuttings for the quantification of thinly bedded source rock, these correlations are extremely encouraging and suggest that the source rock is widespread, both laterally and across the depositional dip.

Not all the formations have been adequately sampled; for example, the Lefroy Formation is very poorly controlled. Based on geological principles, the Lefroy Formation may have been deposited in the portion of the basin that contained the deepest water with the potential for extensive areas of quiet anoxic deposition. Thick source rocks of large areal extent could have been deposited. As the Lefroy Formation probably interfingers with the Townsend Quartzite, lateral migration of expelled petroleum into these sands, if they still retained porosity, would have been relatively easy. Shale or salt seals could be effective in this petroleum system.

Source-rock maturation and petroleum generation

The maturity of the strata is shown in the Appendix. The results show few consistent depth–maturity trends, thus casting some doubt on the reliability of the measurements. This reliability is further challenged by comparison of the equivalent vitrinite reflectance and other maturity indicators such as T_{max} and the production index. The Empress 1A values are compatible for the depths tested on all three plots, and the Yowalga 3 values are compatible for equivalent vitrinite reflectance and production index, but the T_{max} maturity is incompatible. Disappointingly, production index and T_{max} values are not supportive of each other, with the production index suggesting much higher levels of maturity. Nevertheless, the Appendix shows that the bulk of the samples are still in the oil window. Of the samples with equivalent vitrinite reflectance values in excess of 1.5%, most are associated with salt, which because of its excellent conductivity results in elevated local temperatures. With all their inherent inaccuracies, the measured maturities nevertheless indicate that not all the petroleum was generated during the Neoproterozoic.

Matching the present-day formation temperatures, as measured in wells, with the depths and lithologies encountered allows the calculation of present-day heat flow in the Yowalga area. The basic control data and the fit achieved is shown in the Appendix. Though the match is not always excellent, a generally low heat flow of 0.7–0.8 heat flow units (HFU) is calculated in the Appendix, and is supported by a slightly higher value of 0.9–1.1 HFU that was calculated by JNOC (1997, fig. VIII-7). This variability is probably an intrinsic property of the basement underlying the Officer Basin, where different basement types (sedimentary, metamorphic, and igneous) have different thermal conductivities and contain different sources of heat. When this heat flow value was combined with the known burial history of the sediments, the resultant maturation profiles could not be matched by measurements from the wells. Consequently, heat flow in the past must have been higher than at present. Both the JNOC and GSWA studies adopted a graded history, with maximum heat flow in the past and gradual cooling to the present day. The JNOC maximum heat flow is 250% greater than present day, while that of GSWA is only 50% higher.

After calibrating the geothermal history of the area from well control, JNOC undertook detailed petroleum-generation, expulsion, and migration modelling, using sophisticated 2D-modelling at 80 pseudowell locations, and complex source-rock characteristics. The GSWA study involved only a 1D-modelling package for the control wells and six pseudowell locations; however, these points have been carefully chosen as representative of the most deeply buried portions of the basin. The GSWA model assumes a single, simple source-rock of type II with a TOC value of 1%, which is towards the higher end of the source-rock values encountered.

The JNOC modelling was hindered by lack of age control on the timing of deposition, and the timing and magnitude of the erosive phases. For example, JNOC used a date of 1000 Ma for commencement of deposition of the Townsend Quartzite, as opposed to 840 Ma, and used a duration of deposition of the Browne Formation of 200 million years instead of the 30 million years used in this study.

The aim of the GSWA study was to identify the present-day maturation levels in all parts of the Yowalga area, and especially in those intervals identified as containing source rocks, in an attempt to estimate the timing of maximum oil and gas generation. The Appendix shows computer-contoured isomaturity maps of the Yowalga area for five source-rock horizons. The contours are based only on the ten modelled locations, with no geological input. Even with this limited control, a northwesterly trend is evident, with greater maturity towards the north. Geologically, this is a result of the axis of greatest sedimentary deposition passing through the SP 5000 and SP 2030 pseudowell locations. The Empress 1 and 1A location is also a relatively mature area, due to the higher heat flow in this location. The extent and source of this anomalous heat flux remains unknown, but is not unexpected because of the large variations in basement known to be present in the Officer Basin. The source-rock interval in S1 has entered the oil window and some oil has been expelled, but only in the deepest part of the basin (Appendix). The source-rock interval in K1 reached mid-maturity for oil generation only in the north, in the deepest portion of the basin. Early maturity was reached in the north and in an area around Kanpa 1A and Empress 1 and 1A, whereas much of the area (one third) is still above the oil window (Appendix). In the Hussar Formation source-rock interval (H3), almost the entire Yowalga area is within the oil window, with the northern portion of the area well into the oil window and having generated most of its oil potential. The Browne Formation source-rock intervals are almost all within the middle or later portion of the oil window, with some even into the gas window, where they have already generated the bulk of their petroleum potential.

An alternative way of looking at the level of maturity of the major source-rock intervals is to examine their level of maturity and the rates of oil and gas produced over time. Maturation histories for the calibration wells are given in the Appendix. Yields have been calculated for a source rock of type II (typical of that identified in the Yowalga area) with a TOC level of 1%, which falls at the high end of values recorded in the Yowalga area. The maximum level of maturity is found in the Browne Formation (B4) source-rock interval in Empress 1A, where petroleum generation took place over a short time interval at about 750 Ma. Oil was generated at a level of 0.09 g hydrocarbon (HC)/g and gas at 0.017 g HC/g. The

B2 succession (older Browne Formation) reached maturity at about the same time in Yowalga 3 as B4 did in Empress 1A, but the level reached was not as high (an oil value of 0.02 g HC/g), though generation continued over a longer period of time of more than 100 million years. A minor phase of oil generation also took place in the Permian. At the Kanpa 1A location, the Browne Formation source rocks similarly achieved their greatest rate of petroleum generation at about 650–750 Ma, but at a slower rate than in the Yowalga 3 area. There was also minor petroleum generation in the Early Cambrian and Permian.

Maturation histories for the deepest parts of the Yowalga area have been modelled at SP 2030 on seismic line T80-11 (Appendix). Most petroleum generation in the Browne Formation took place over a short period of time at about 750 Ma. After that time, all the oil had been generated, but there was minor gas generation during the Permian. The major petroleum-generation phase for the Hussar Formation was at about 700 Ma, with mainly oil generation, but also some gas. Not all of the petroleum-generating potential was exhausted at that time, and there was minor generation of petroleum during the Permian and Cretaceous. This lower maturation level and later generation is a reflection of the burial history, where the oil window was entered later, and additional burial pushed it even further into the oil window. The overlying Kanpa and Steptoe Formation source-rock intervals suffered less burial, which resulted in petroleum generation only beginning in the Permian, and being renewed in the Cretaceous due to further burial. These source rocks remain in the early oil-generation window and have only yielded part of their oil and gas potential. Geochemical analysis indicates that these rocks are currently generating petroleum in parts of the Yowalga area.

Reservoir potential

The presence of both carbonate and siliciclastic reservoirs in the Officer Basin increases the opportunities for porosity creation. The Lennis, McFadden equivalent, Lupton, and Lefroy Formations, and the Townsend Quartzite contain only siliciclastic reservoirs, whereas the Steptoe, Kanpa, Hussar, and Browne Formations contain potential hydrocarbon reservoirs in both quartzose and carbonate lithologies.

Thick sandstone beds have been intersected in wells and have log-evaluated porosities as high as 15–20%, but no measured permeabilities above 2 millidarcies (md) (Fig. 18a). The fully cored Empress 1 and 1A has allowed the measurement of both porosity and permeability for each of these formations, resulting in values in excess of 20% porosity and 1 Darcy (D) permeability (Fig. 18b). Some virtually unconsolidated sands have been encountered in Empress 1A. Comparison of measured and log-derived porosity in Empress 1 and 1A shows that log-derived values are reliable (Stevens and Apak, 1999, plate 1). Most of the carbonate beds are dolomite, but if they were originally calcite no porosity associated with this transformation appears to have been created. The replacement is mimetic

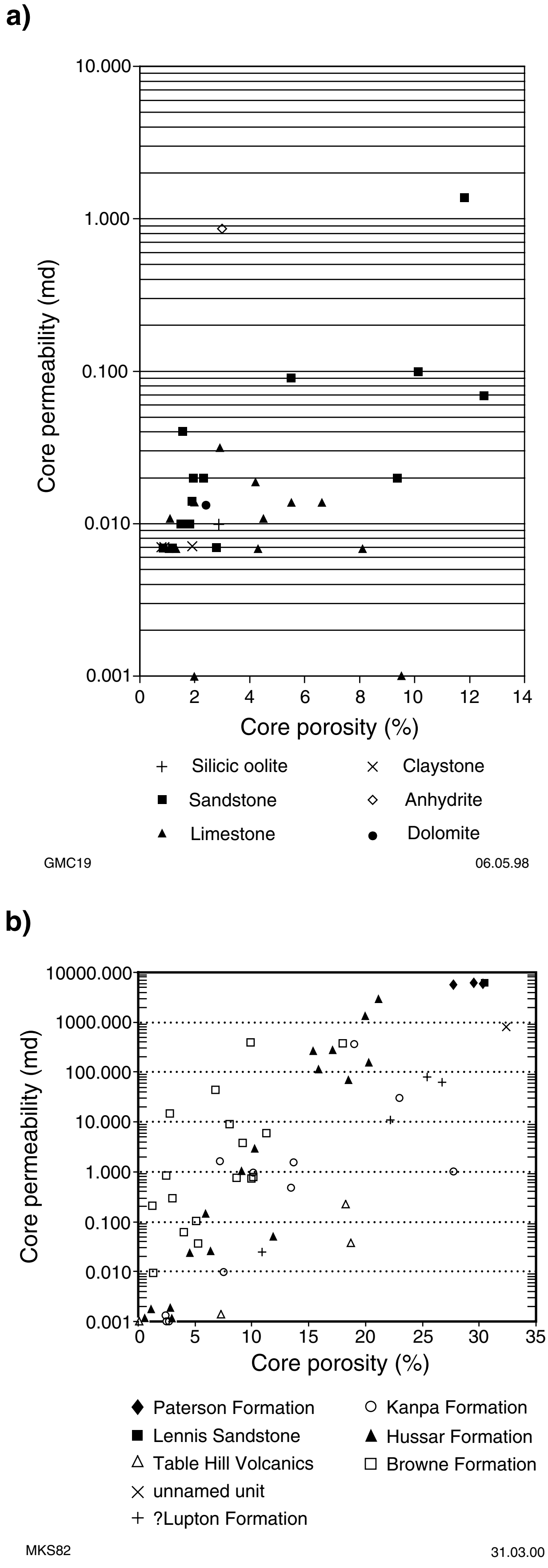


Figure 18. Comparison of reservoir porosity and permeability data: a) Officer Basin prior to drilling Empress 1 and 1A; b) in Empress 1 and 1A

and complete down to the finest detail. Other opportunities for the creation of porosity exist in the evaporitic facies deposits, where solutions of halite or other evaporites may result in leached secondary porosity.

Townsend Quartzite

In outcrop, on the southern edge of the Musgrave Complex, the sandstones are strongly lithified, thus leading to their classification as a quartzite. In thin section, an extensive syntaxial overgrowth can be seen on the quartz grains, which completely occludes the porosity (Jackson and van de Graaff 1981, fig. 18). The extent of the overgrowth indicates that this must have taken place at an early stage. This is shown by overgrowth into what must have been large pores, and by the fact that later compaction has resulted in grain penetration through the overgrowth. This rock would not be an effective reservoir.

In Kanpa 1A, cutting samples were examined in thin section, and showed a similar quartzite lithology that was tightly cemented either by silica or by an even earlier phase of anhydrite or carbonate cement (Shell Company of Australia, 1983a,b,c). Log evaluation indicates a porosity of 1.4%. Because of its diagenetic history and its limited distribution, the Townsend Quartzite is not regarded as a primary reservoir target at this stage, unless depositional porosity has been preserved.

Lefroy Formation

Apart from an outcrop south of the Musgrave Complex, this formation has only been intersected in the Empress 1A well. This formation consists of siltstone and claystone. The Lefroy Formation is not regarded as a reservoir objective.

Browne Formation

The Browne Formation consists primarily of mixed carbonate – siliciclastic strata and a few thin-bedded sandstones. A thin section of these sandstones from the Empress 1A core shows quartz grains in point contact and with very thin dust rims and sporadic carbonate cement, but all the remaining porosity is occluded by coarse halite cement (Fig. 19a). Based on its relatively high proportion, the halite must have been introduced early in the burial history. This rock has no reservoir potential. Because the halite is very soluble, fluids travelling along migration paths such as fracture systems may dissolve the salt, thus creating an excellent reservoir. Unconformities would also be zones more likely to contain such secondary reservoirs.

The carbonate content of this unit varies from 53% in Yowalga 3 to 18% in Empress 1A. The carbonate is dolomite that has mimetically replaced the original calcite down to the finest detail (Fig. 19b). All of the typical limestone lithotypes of micrite, packstone, grainstone, and boundstone are recognizable in the unit, as well as textural features such as fenestrae (Figs 19b and c). Most of the carbonate has been deposited in shallow water, and subjected to frequent emergence. Unfortunately, all of the initial depositional porosity has been occluded at an early stage by cement-grain rims, equant cement-cavity fillings, and anhydrite or halite cements, thus resulting in a tight non-reservoir rock. The porosity is low, with most log-derived values being around 2%. However, log-calculated values up to 15% have been determined in Yowalga 3 (Shell Company of Australia, 1981), and measured porosities of 9.5% were recorded from some cores. In Empress 1A, core porosities of up to 16% were measured, but inspection of the plug offcuts in thin section showed a high halite content. It is believed that the high porosity and permeability values probably resulted from the accidental removal of at least some of the halite during the preparation of the plugs (Stevens and Apak, 1999).

Prime exploration targets would be locations near unconformities where surface leaching could be extensive, thus creating secondary porosity. Any migration path containing fluids capable of dissolving dolomite, anhydrite, or halite may result in secondary leached porosity. No means of predicting such porosity is known at this time.

Another diagenetic phase recognized in this formation is silicification of the initial carbonate phases. Unfortunately, the silicification is mimetic down to the finest scale, with chert, chalcedony, and megaquartz replacing carbonate. Partial silicification and subsequent leaching can be proposed as a porosity-creation scheme, but this has not yet been found in the area and would require additional information before a predictive model can be established.

Hussar Formation

The Hussar Formation is a mixed siliciclastic – carbonate sequence. The carbonate content ranges from 28% in Yowalga 3 to 16% in Empress 1A. The sandstone ranges from 24% in Yowalga 3 to 43% in Empress 1A, and argillaceous sediments from 53% in Kanpa 1A to 42% in Empress 1A.

As there is more sandstone than carbonate in the formation, the sandstones are the main reservoir objective. Shell Company of Australia measured maximum log porosities of 15–17% for sandstones in their three wells of Yowalga 3, Kanpa 1A, and Lungkarta 1 (Townson, 1985). In the fully cored Empress 1A, log-derived porosities confirmed this range, with values reaching 20%. When compared with core and plug results, log values have proven to be reliable estimates. Permeabilities in Empress 1A range beyond 1 D, but plug and mini-permeameter values are approximately 100 md. Although individual sandstones are present, the beds are usually stacked into thicker sandy intervals of up to 50 m in thickness. They form a realistic reservoir target for petroleum exploration in the Officer Basin.

Thin-section studies in Empress 1A have shown that the sandstones exhibit burial compaction effects, and contain occasional grains with concavo-convex contacts, but the small amount of syntaxial quartz overgrowth proves that compaction was not too severe (Fig.19d).

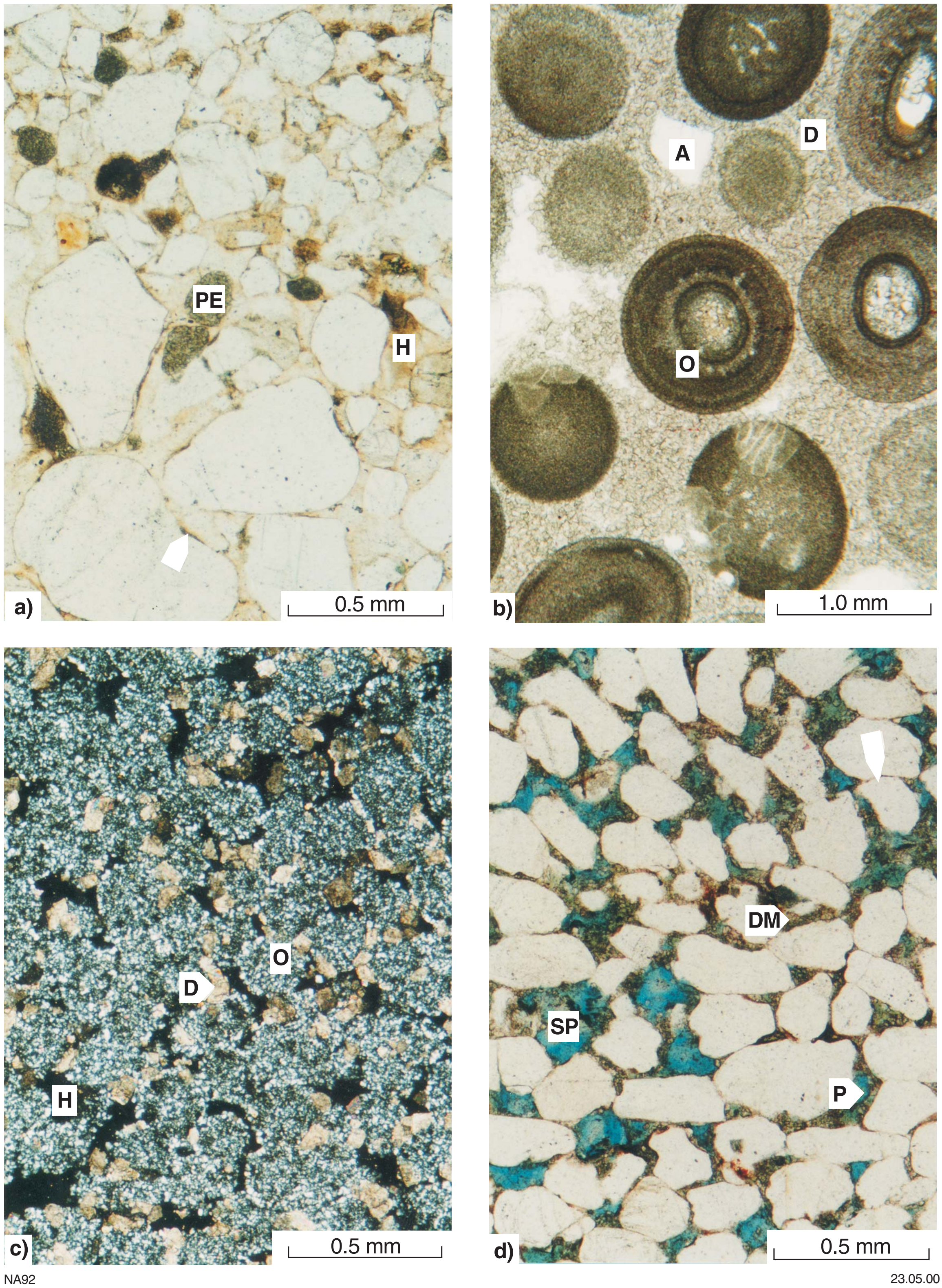


Figure 19. **Thin sections from Empress 1A core: a) sandstone from the Browne Formation, showing little compaction, thus proving that the halite cement (H) was an early deposit. There is no present-day porosity. The section contains peloids (PE) and microspar rims (arrowed); b) oolitic (O) grainstone from the Hussar Formation. The original mineralogy was calcite that has now been mimetically altered to dolomite (D), with no creation of porosity. Anhydrite (A) filled the original pore space before dolomitization took place, and there is no present-day porosity; c) silicified peloidal grainstone from the Browne Formation. Original peloids (O) have been silicified, but are still recognizable, whereas intergranular cement has been dolomitized (D). All remaining intergranular areas are filled by halite (H). Cross-polarized light; d) sandstone from the Hussar Formation, showing only partially compacted sandstone, with slight grain interpenetration and minor syntaxial overgrowth. Minor carbonate cement (DM) has reduced the present-day porosity (P) to 10.5%. Minor secondary porosity (SP) is also present**

Carbonate cementation, which occurs as a granular filling within the porosity (Fig. 20c), is a more severe porosity-reduction agent. No coarse poikilotopic fabric has developed. Carbonate occlusion of the porosity ranges from incipient small patches to complete obliteration over substantial areas. This may explain the wide range of measured permeabilities.

Minor porosity creation is noticeable in the leaching of some feldspar grains (Fig. 20c), but as feldspar only forms a small proportion of the rock the resulting porosity increase is small. Porosity occlusion by clay deposition in the pores is rare, but where it is present it may be extensive. Its timing is uncertain.

The Hussar Formation contains a smaller percentage of carbonate than the Browne Formation. In the Hussar Formation, the carbonate is not present in thick sections, and it contains the same shallow-water to emergent facies, lithotypes, and evaporites as the Browne Formation. In Empress 1A, halite is absent, but anhydrite is common. As in the Browne Formation, the carbonate consists of dolomite that has stoichiometrically replaced calcite, with no resultant porosity. Log-derived porosity is approximately 1–2%, which has been confirmed by plug measurements. Permeabilities are virtually zero.

Secondary porosity development as a result of the dissolution of anhydrite has been observed in several formations in the Empress 1A core. This type of secondary porosity is most strongly developed in Empress 1A core along the karstified surface of the Steptoe Formation. The association of regional unconformities and hydrocarbon accumulations is well known and widely published. Karstification along regional and local unconformities in the Officer Basin provides additional petroleum exploration targets.

Kanpa Formation

The Kanpa Formation has only been completely penetrated in Kanpa 1A and Empress 1A. It is a mixed siliciclastic – carbonate sequence, with a low sandstone content. In Kanpa 1A, the formation contains 30% carbonate rocks and 28% sandstone, whereas in Empress 1A it contains 37% carbonate rocks and 17% sandstone. Argillaceous siltstone and claystone make up the remaining lithologies of the formation.

As in the older formations, the carbonate is a shallow-water facies with evidence of emergence, desiccation, and erosion. The formation does not contain halite, although anhydritic zones are present. The dolomitization is again stoichiometric, with no porosity formed during the transformation. During log evaluation, a 6.5 m interval of dolomite with 14.9% porosity was recognized in Lungkarta 1, but generally log porosity is less than 5% (Shell Company of Australia and Schlumberger, 1985). This low carbonate porosity has been confirmed by plug measurements in Empress 1A. Permeability measurements for plugs in Empress 1A were virtually zero. The carbonate rocks can generally be regarded as non-reservoir rocks; however, location on an unconformity could result in substantial leached secondary porosity.

Within the Kanpa Formation, sandstone is only a small proportion of the formation and is present as sections less than 10 m thick. Consequently, they are not attractive reservoir targets. In Empress 1A, log-derived porosities reach up to 15% and are supported by plug measurements, although plug permeabilities are only in the order of 1 md.

Examination of thin sections from Empress 1A shows that the sandstone commonly contains a proportion of carbonate grains. These are readily deformed, resulting in compaction and probably releasing carbonate that may form an intergranular cement that further reduces porosity and permeability (Figs 20a and b). Quartz grains show point-to-point contact only. In the cleaner sandstone, porosity is reduced by a clay cement, which may form rims to the grains and leave some porosity, or may completely fill the porosity. The carbonate and clay cements are the main reason for the low permeability values, as they tend to block the throats of the pores. Some of the feldspar grains show severe leaching, which has resulted in some porosity enhancement, but their isolation results in generally ineffective porosity.

Steptoe Formation

The Steptoe Formation has only been penetrated in Kanpa 1A and Empress 1 and 1A. In both cases, the formation is truncated by an unconformity. Correlation on seismic lines shows that there was a substantial section of the Steptoe Formation deposited above the Kanpa Formation (Plate 1).

The Steptoe Formation is a mixed siliciclastic – carbonate deposit. It consists of a basal argillaceous unit overlain by interbedded sandstone and carbonate deposits. In Kanpa 1A, the formation contains 30% sandstone and 39% carbonate rocks, whereas in Empress 1 and 1A it contains more sandstone (40%) than carbonate rocks (28%).

In Kanpa 1A, 128 m of sandstone, showing porosity in excess of 15%, was recognized from electric logs (Shell Company of Australia 1983a,b,c). Appropriate log coverage is absent in Empress 1 and 1A, but a single measured porosity was in excess of 22%, with a permeability of approximately 30 md. The Steptoe Formation sandstone is a reservoir objective at a depth of 570 m.

As in the older formations, the carbonates are shallow-water sediments, with evidence of emergence, desiccation, and erosion, although evaporites are absent. The dolomitization is again mimetic, with no porosity formed during the transformation. Only a single plug was cut in the Steptoe Formation carbonate, which gave a low porosity and virtually a zero permeability when tested. Numerous permeameter readings indicate a permeability of around 0.1 md. These carbonate rocks are not an exploration target unless secondary porosity, such as that near an unconformity, can be postulated. Significant vuggy porosity and karsting were observed in Empress 1 and 1A, although in this drillhole all the large karsts were filled with sediment.

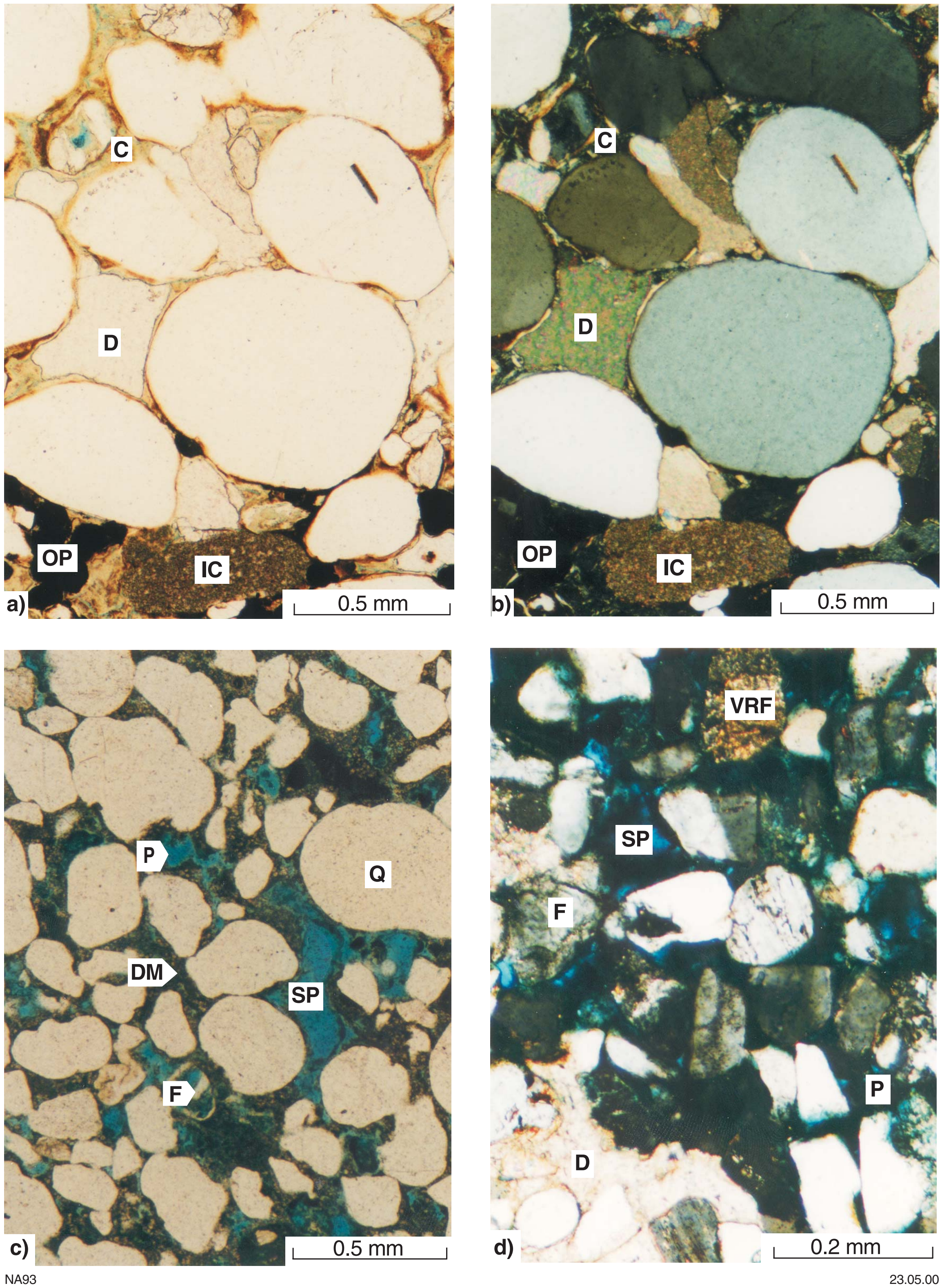


Figure 20. Thin sections from Empress 1 and 1A cores: a) sandstone from the Kanpa Formation, showing well-rounded, equant, monocrystalline quartz grains rimmed with clay (C) before a later phase of carbonate cement , now dolomite (D), occluded all of the remaining porosity. Some ductile carbonate lithics (IC) and opaques (OP) are also present; b) the same view as (a) under cross-polarized light; c) sandstone from the Kanpa Formation, showing well-rounded quartz grains (Q) in point contact with each other. A carbonate cement (DM) has reduced the porosity to 9.6% and the permeability to 0.5 md. Some leached porosity has been created in the feldspar grains (F) and unidentifiable grains (SP); d) sandstone from the Lupton Formation, showing both angular and rounded quartz grains in point contact. A carbonate cement, now dolomite (D), has severely reduced the porosity in part of the slide, while excellent porosity (P and SP) remains in the rest of the slide. Feldspar grains (F) and volcanic rock fragments (VRF) are minor components

Lupton Formation

The Lupton Formation consists of siliciclastic glacigene strata dominated by mass-flow sands. Substantial lithological changes have been observed at various locations, but generally the dominant lithology is sandy. The 200 m-thick section in Empress 1 and 1A consists mainly of sandstone, with a number of mudstone beds about 5 m thick. Measured core porosity ranged between 10.9 and 32%, with an average for the five values of 23.5%. Permeability ranged between 0.04 and 831 md. Additional minipermeameter values were between 200 and 2000 md (Stevens and Apak, 1999). A single thin section (Fig. 20d) showed excellent porosity, but some areas have carbonate cement. This may explain the variation in porosity and permeability measurements, with the variable carbonate cement reducing the reservoir quality.

McFadden Formation equivalent

In the Yowalga area, this unit has only been intersected in Kanpa 1A and Lungkarta 1. On seismic data, it has been estimated to reach a thickness of 1200 m (Townson, 1985), so the thin intersections observed in wells may not be representative of the bulk of the formation. Thin sandstone beds with a porosity of 18.9% have been calculated from logs in Kanpa 1A (Shell Company of Australia, 1983a,b,c).

Seals

Seals in the Officer Basin need to be considered from a number of perspectives. Seals can act as local seals to four-way dip-closed traps, as local seals in fault-controlled traps, as lateral seals in stratigraphic traps, as regional seals controlling the migration paths of petroleum, and as lateral regional barriers to petroleum migration. The effectiveness of a seal over time is also important, as thermal maturation modelling shows that a petroleum charge has been available in the Officer Basin since the Neoproterozoic and would need to have been contained for more than 700 million years (see **Petroleum generation**). The effectiveness of seals in the Officer Basin must be considered for both oil and gas. Previous exploration drilling has located both oil and gas in the basin, and geochemical modelling shows both fractions have been generated since 700 Ma and continue to be produced.

Within the Officer Basin, most of the formations contain lithologies that would make effective seals at all scales. All formations contain both carbonate and shale that are suitable for seals. Thinner intervals act as local seals, and thicker packages have a more regional effect. The carbonate rocks are dolomitic and have no porosity (see **Reservoir potential**). They could form an effective seal, but their brittle nature increases the risk of them losing their integrity in a fold trap. Similarly, in a fault-seal trap their brittle nature results in a higher risk of carbonate losing seal potential, from the point of view of both cross-fault sealing and fault-plane gouge sealing. The best shale seals are those that were deposited at the base of the parasequences at the maximum flooding surface. These units reach thicknesses of over 100 m in the Hussar Formation in Kanpa1A, and can be correlated between wells and picked on seismic lines for hundreds of kilometres across the basin. These could form effective seals to individual traps, but more importantly, they could act as a control on migration paths for fluids.

The Browne Formation contains massive units of halite, but individual salinas may have had a more local distribution because not all the salt packages can be correlated between all of the wells. This is probably a depositional constraint rather than a result of salt flow. The lateral extent of the salt is adequate for sealing all the structural traps, and such an excellent seal would control migration paths over a large portion of the basin.

Salt walls penetrate from the lower part of the Browne Formation through most of the overlying section, and even reach the surface. They extend laterally for over 100 km, and have been mapped from seismic data. Salt walls provide effective barriers to petroleum migrating from structural deeps, causing a migration shadow updip behind them. Yowalga 3 may thus have had the access to its kitchen considerably reduced by a salt wall less than 20 km to the north (Fig. 3). The timing of these walls with respect to the generation of petroleum is important.

Traps

Because of the geographic isolation, lack of infrastructure, and harsh climatic conditions, petroleum accumulations within the Officer Basin need to be substantial in order to be commercially viable. The current availability of low-cost, alternative gas supplies to the surrounding markets also indicates that oil would be the favoured petroleum product. It was proposed to carry out a study to identify what would be the minimum size of a commercial accumulation. However, the swift obsolescence of a similar study for the South Australian portion of the Officer Basin (Alexander and McDonough, 1997) proved that each company would need to use the currently prevailing parameters in a 'just-in-time' evaluation to reach a meaningful conclusion. Alexander and McDonough (1997) concluded that oil reserves of 20 million barrels would be commercially attractive under their constraints.

The presence of salt within the Officer Basin has resulted in a wide range of possible trapping configurations. Warren (1989) has defined 22 possible salt-related traps, based on structure and porosity development, or occlusion. Many of these could apply in the Yowalga area. In petroleum-rich Oman, the Ara Salt is the principal seal for nearly all of the accumulations, and is considered a critical parameter for petroleum entrapment (Gorin et al., 1982). With sediments of similar age in the Officer Basin, salt is expected to have the same significance. All the structures tested by petroleum exploration wells in the Yowalga area have been salt-related. No effort has been made to quantify the size of the traps within this area. Structural traps are inadequately controlled by seismic data (Fig. 3) and do not allow for meaningful calculations. Stratigraphic traps also suffer from the same lack of control, but they have the potential to be very large. The main play types are summarized in Figure 21, and a brief outline for each type is presented below.

Fault traps

Normal faults

Normal faults are present in the Yowalga area. The dominant strike to 145° is orthogonal to the dominant dip direction, and provides a suitable environment for trapping migrating hydrocarbons. Within Supersequence 1, there are numerous thick shale intervals that would be suitable as cross-fault seals. Shaly intervals of approximately 100 m thickness are present at the base of the Hussar and Kanpa Formations, and throughout the Browne Formation. These intervals would be good seals on faults with a throw of less than 100 m. Thinner zones would be effective for faults with less throw. The thick salt beds in the Browne Formation make excellent seals. Both the salt and shale lithologies would also make good fault-gouge seals by improving the retention properties of traps. Tight dolomite intervals could be effective as cross-fault seals, but their brittleness is more likely to result in a fault-fracture system that would leak. The possibility of stacked pays could enhance the total volume of traps.

Fault traps related to the Areyonga Movement have favourable aspects with respect to charge timing, but the possible reactivation of these faults during later tectonic phases could reduce their sealing potential.

Thrust faults and folding

Numerous thrust faults are present within the Supersequence 1 formations. They have typically initiated within the Browne Formation salt units, but penetrate upwards into the overlying formations. They may create drag rollover structures within the units they penetrate, or deform the overlying units into anticlinal features (Fig. 21). The resultant structures may be large (Fig. 3). With the presence of salt on the fault plane, fault-plane sealing could be excellent, and even in its absence an improved undertanding of the geological succession makes it possible to quantify the effectiveness of cross-fault seals. A serious risk is that deformation of the sediments will result in numerous tensional crest faults that may leak. Another risk would be reactivation of structural growth during subsequent tectonic phases, which would release any hydrocarbon accumulation.

Drape folding

Salt movement within the Browne Formation (by solution, withdrawal, or injection) has resulted in numerous irregularities in the shape of the Top Browne horizon. These gentle folds affect all the younger Supersequence 1 units and can be of substantial size (Fig. 3). The possibility of multiple pays is very likely, but there is a risk of tensional crest faults being created as the overlying sedimentary beds are flexed. As most of the salt flow appears to have taken place by the time of the Areyonga Movement, the timing of the formation of such structures is favourable with respect to charge.

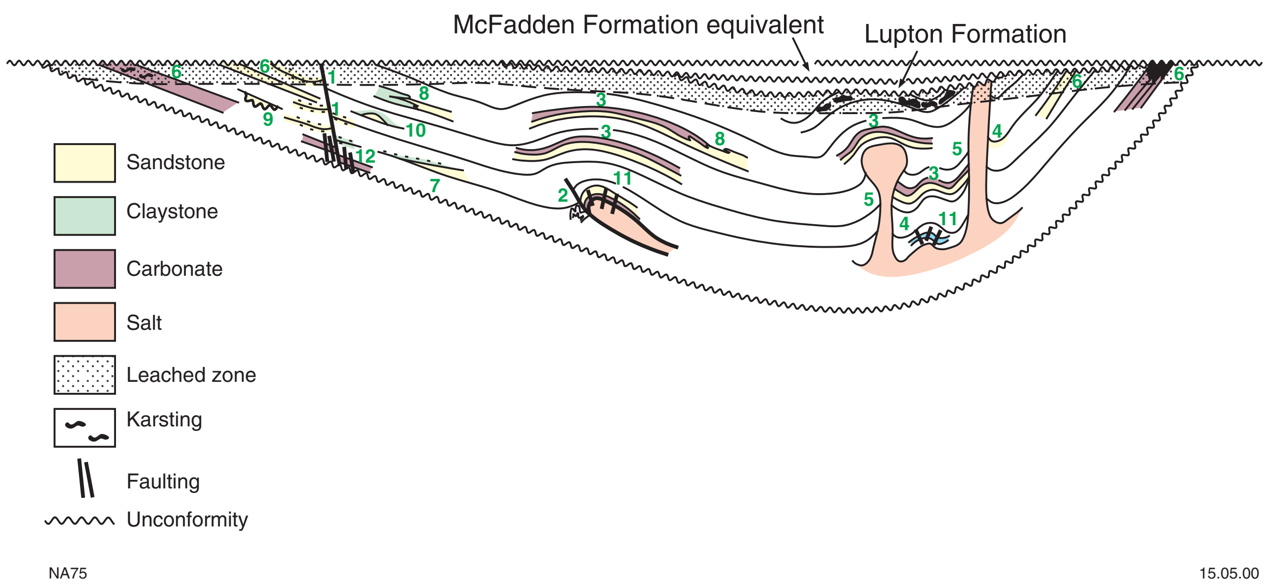


Figure 21. Schematic section of play types in the Yowalga area: 1) normal fault trap; 2) drag fold on a salt-lubricated thrust; 3) drape over a salt-movement high; 4) tilted salt-abutment trap; 5) salt-wall abutment trap; 6) leached-zone porosity enhancement in sands and carbonate rocks; 7) stratigraphic pinchout trap; 8) stratigraphic facies-change trap; 9) erosional channel filled by reservoir sands that are sealed by a transgressive seal; 10) isolated offshore sandbar within shale or carbonate rocks; 11) fractured carbonate rocks in a flexured area; 12) fractured carbonate rocks in a fault zone; 13) possible compressional folding proximal to the Musgrave Complex thrusts

Lateral salt seals

Piercement of the stratigraphic section in the Yowalga area by diapiric salt usually results in an upturning of the beds towards the salt (Fig. 21). Highs abutting the salt make excellent traps (Fig. 3). Timing of the diapiric phase with respect to petroleum charge is good, and the presence of salt assures an effective seal that is able to maintain its integrity over a long period.

Salt walls are a variant on this theme. The presence of salt walls has been discussed in the section on **Seals**. Traps formed by this mechanism have the potential to cover large areas and contain multiple pays.

Fractured reservoirs

In the Zagros Basin in the Middle East, the main control on porosity is fold-related fracturing of carbonates (Beydoun et al., 1992). Without this fracturing, the porosity of the carbonates is typically less than 5% and their permeability is about 1 md. Wells that do not intersect fractures are dry. Reservoir capacity and performance have been sufficiently enhanced by fractures to result in the production of up to 80 000 barrels of oil per day. Carbonates within the Officer Basin are likely to contain fracture systems because they are sometimes tightly folded. Fracture zones that have developed during the thrusting associated with these folds are also possible. Although the carbonates here are not as thick as the Asmari Limestone of the Zagros Basin, the possibility of stacked pays increases the potential reserves.

Fracture zones associated with any of the other faults also have the potential to create reservoirs; however, their extent is probably limited.

Compressive folding

In the Yowalga area, the bounding orogen is the Musgrave Complex. No seismic data and very little well data are available for the Officer Basin region adjacent to the Musgrave Complex. However, outcrops of the Officer Basin adjacent to the Musgrave Complex, and seismic data from South Australia, demonstrate that foreland-basin style compressive folding is common along the northern margin of the Officer Basin.

Stratigraphic traps

Stratigraphic traps may represent significant opportunities for the discovery of hydrocarbons in the Officer Basin. A number of such traps are discussed below.

Unconformity truncations

There are large areas adjacent to salt-injection features and along basin margins where the sedimentary sequences have been tilted and severely eroded. During an erosive period, a vertical leached profile may develop and result in increased porosity (Fig. 21). Leaching out of the more soluble components such as halite, anhydrite, and carbonate from sandstone and carbonate, and even possible development of karsting within carbonates, may create porosity. Evaporite cements and nodules are common within all of the Supersequence 1 formations. They are most abundant in the Browne Formation, but unfortunately this unit has a low sand content and the main objective would be the carbonate. Porosity could have developed in either sandstone or carbonate rocks in the Hussar, Kanpa, and Steptoe Formations.

Another strength of the unconformity play is the fact that unconformities are commonly regional migration paths for fluids being expelled from compacting basins. These fluids could enhance porosity by dissolving soluble components and could also transport petroleum into the newly created trap.

A weakness of the Areyonga Movement truncation is that the Lupton Formation, which is a poor seal, overlies much of the unconformity. The principal lithology is sandstone that, although of glacigene provenance, appears to be an inadequate seal. In Empress 1 and 1A, porosity of the basal sandstone was in excess of 25% and permeabilities ranged between 100 and 1000 md, which results in an ineffective seal. More work is required to establish the distribution of the Lupton Formation, but in areas where it is absent the McFadden Formation equivalent may provide an adequate seal. In Kanpa 1A, the bottom 29 m of the McFadden Formation equivalent contain massive porous sandstone. The next 70 m above this section are massive shale that would be an effective seal. Seismic control is still inadequate, and our understanding of charge timing, potential reservoirs, and seal distribution for this play is uncertain. However, such traps could contain large petroleum accumulations.

Pinchout traps

This study provides direct evidence for pinchout traps in the Yowalga area. Differential subsidence in the Officer Basin has resulted in downlap and uplap of units providing opportunities for pinchout traps (Fig. 21). For example, the bottom two parasequence sets of Sequence B (Browne Formation) in Yowalga 3 and Kanpa 1A are not present in Empress 1A, and S2 of Sequence S in Kanpa 1A is absent in Empress 1 and 1A. The key components for an effective trap of this type are a reservoir pinching out between a top seal and basal seal. From the point of view of charge, the timing of such traps is excellent, and there is a good chance that such a structural configuration could be maintained over a long period of time. Preservation potential in these traps is excellent.

Facies changes

An improved understanding of the stratigraphy has shown that lateral facies changes are present in the successions (Fig. 21). For example, the dolomitic zone in the H 1 parasequence set present in Kanpa 1A (2260 – 2400 m) is absent in the equivalent intersection in Empress 1A. In Kanpa 1A, shaly sediments that would make good top and bottom seals overlie the carbonate. In Empress 1A, the equivalent overlying strata are sandy. If these sandy facies extended to Kanpa 1A and overlaid the carbonates, this would invalidate the top seal. Sandy intervals may also terminate against suitable shale or carbonate seals. Isolated shoreface sandstones, such as an offshore bar within shale, are also possible stratigraphic traps (Fig. 21). The early timing of such traps is excellent with respect to charge, and the stable, low-angle ramp configuration of most of the Yowalga area should enable the maintenance of trap integrity over long periods of time.

A possible variant of this type of trap is the occlusion of porosity by evaporites in more marginal settings. There are numerous horizons where halite and anhydrite have been formed in desiccation zones, plugging the porosity of the sediments either during, or just after, deposition. Such traps are also early with respect to charge and could be expected to retain any accumulation over a long period.

Erosive channels or valleys

Frequent emergence is well documented in much of the Supersequence 1 strata, and any channels could later be filled with high-energy, reservoir-quality sediments and sealed by the subsequent transgressive shale (Fig. 21). Again the timing with respect to change is excellent, and the retention of petroleum in this very stable area is likely to be good.

Prospectivity

The potential for the discovery of substantial petroleum reserves in the Officer Basin has not yet been proved, but the authors believe it is good. The present study has applied modern depositional, geochemical, and sequence-stratigraphic concepts, and has refined the prediction of the distribution of the various components required to define petroleum systems that may be present in the Officer Basin. Because there are so few wells, and they are typically poorly located structurally, and frequently have not reached key objectives, the lack of success is not surprising. However, the minor shows encountered prove that petroleum systems do exist. Key wells, like the fully cored Empress 1 and 1A, have provided information previously unavailable from conventional oil exploration.

The lack of source rocks was seen as a negative factor in earlier assessments of the petroleum potential of the basin. However, from additional information obtained through the GSWA Petroleum Initiative, and a more discriminating analysis of the available database, the presence of source rocks can now be confirmed in most of the Supersequence 1 formations. The intervals with identified potential are only thin, but they prove that favourable conditions for source-rock accumulation were present. Their lateral persistence indicates that the conditions controlling their deposition were regional, rather than local. Greater development of source rocks is possible in untested parts of the basin. All of the source rocks are very similar, and contain type II kerogen with both oil- and gas-generating potential.

Geochemical modelling has suggested that the timing of oil generation was very early, and hence retention of petroleum was considered a problem. A better understanding of the chronology of the basin evolution has reduced the expected retention time by showing that peak generation was later than previously believed. Measured maturity indicators show that much of the stratigraphic section has still not progressed very far into the oil window, and that only a small proportion of its oil potential has been realized. However, since there has not been substantial burial since the deposition of Supersequence 1, this has resulted in little increase in the maturity of the source rocks, and hence little generation of new oil. Some extra oil generation has taken place where Supersequence 3 and 4, and Permian or Cretaceous sedimentary rocks have been deposited, and regions where the Permian and Cretaceous rocks are thickest are the best places to search for such late-stage oil pulses. For younger accumulations, remigrated petroleum should also be considered.

Another factor affecting maturation is heat flow. From the few well-control points available, substantial differences in present-day heat flow have been identified across the basin. This factor would affect the timing and level of maturity reached in various portions of the basin, but more information is required before such considerations can be applied in detail to individual source rocks. Similarly, geochemical modelling shows that heat flow in the past has been substantially higher than that measured in the present. Some apatite fission-track analyses have been carried out, but no convincing timing for heat flow, or its magnitude within the basin, is currently available. The new tectonic history presented in this Report differs substantially from earlier concepts with respect to the timing and magnitude of the various phases, and this would also affect the timing of peak heat flow periods.

Although many uncertainties still exist, we can now make a number of generalizations about petroleum generation in the Officer Basin; for example, early and high maturation in basin deeps can be compared to lower and later levels, which may be important with respect to the availability of a structure on the basin flanks. For specific areas, when plays are being considered, we can construct models with a range of parameters that define their petroleum-generation potential, and hence select the most favourable kitchens.

Reservoir presence and quality have not been considered a problem by previous workers in the Officer Basin. However, the presence of carbonate rocks, as well as siliciclastic units, within the sedimentary succession opens up a very large range of possible porosity types. The Empress 1 and 1A cores have provided additional insights and have resulted in a better definition of reservoir types and quality. In this well, comparison of log-derived porosity with measured core data has now proven that log-derived porosity values are reliable. Comparison of measured permeability and porosity has allowed the establishment of a transform between the two, thus better defining reservoir quality (Stevens and Apak, 1999). Diagenetic sequences of porosity destruction and creation have been recognized from thin sections of the core. Adequate reservoirs have now been proven and, with our models, can be predicted elsewhere.

The Townsend Quartzite is not regarded as a reservoir target, as none of its sandstone beds are of reservoir quality. The Lefroy Formation is poor in sand, and hence is not a reservoir target. Sandstone is also thin and uncommon in the Browne Formation, but carbonates and evaporites are present in significant quantities and have some potential for reservoir development. The carbonates have been dolomitized without any porosity formation, but secondary porosity could develop as a result of fracturing during flexure or by solution during erosion (karsting). The evaporites (halite and sulfates) are prone to solution, which may result in leached porosity. The Browne Formation, where such secondary porosity has developed, is the oldest reservoir target.

The Hussar, Kanpa, and Steptoe Formations all contain sandstone with reservoir potential. The best reservoir-quality sandstone is present in the Hussar Formation, which contains aggregates of sandstone over 50 m thick. There are good porosities and permeabilities of 100 md–1 D in this formation in Empress 1A. These three formations also contain significant carbonate that is similar to carbonate in the Browne Formation. They have minor primary porosity, but show potential to develop secondary porosity. All three formations have reservoir potential in their sandstones and carbonates, and multiple pays are likely. The Lupton Formation is a siliciclastic sequence containing sandstone with porosities of up to 30% and permeabilites in excess of 1 D. These sandstones would be a drilling target in areas where they are thick. The MacFadden Formation equivalent is not well represented in drilling, and to date only thin sandstone has been identified. These sandstones have reservoir potential, and would be a target in thicker sections.

Because of their thickness and lithology, seals have a high potential for petroleum in the Officer Basin and are present at all levels in the section. The best seal is salt, which because of its plasticity has excellent retention properties. Substantial thicknesses of salt are present in the Browne Formation. Thick shale is present in all Supersequence 1 units, and may be over 100 m thick at the base of parasequence sets. These shales would be excellent as both top and lateral seals. In fault traps, they have the potential to act as fault-gouge or cross-fault seals, wherever the fault throw is less than their thickness. Carbonate can be an effective seal, but it is prone to fracturing in deformed areas. Salt, shale, and carbonate units have a large lateral extent in the basin, and also need to be considered as significant controls on the migration of petroleum. The large salt walls are unconventional controls that may form effective barriers to the lateral migration of petroleum. Other local seals that could result in petroleum accumulations are diagenetic seals, dolomitization, and evaporite deposition.

A wide range of trapping configurations is present in the Yowalga area, including depositional stratigraphic traps, folds, faults, and unconformity traps. The presence of salt further enhances the trap potential of the area, as it is associated with large accumulations elsewhere in the world. There have been very few valid structural tests to date, and all have been associated with salt, thus leaving many other plays untested.

The ultimate petroleum potential of the Officer Basin still remains to be proven and it may be very significant.

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Appendix

Petroleum source-rock potential and maturation history of the Yowalga area

(by K. A. R. Ghori)

Geochemical database

The evaluation of source rocks in the Yowalga area is based on geochemical analyses of samples from petroleum and mineral wells drilled in the Western Australian part of the Officer Basin. The geochemical data were generated during three phases of exploration drilling. The data from the first two phases (1965–66 and 1980–84) are contained in open-file company reports (Perincek, 1998). The data from the recent phase (1995–99) are from two sources: geochemical analyses of samples from existing wells by Japan National Oil Company (JNOC, 1997), and those obtained from new Geological Survey of Western Australia (GSWA) stratigraphic coreholes, as well as existing GSWA samples (Ghori, 1998a,b, 1999; Hegarty et al, 1988). During the last phase of analysis, Geotechnical Services Pty Ltd tested for total organic carbon (TOC) and Rock-Eval pyrolysis, and Keiraville Konsultants Pty Ltd provided the organic petrology.

This study utilizes a significant number of new analyses for TOC (1952), Rock-Eval pyrolysis (617), and organic petrology (82) that are available from the JNOC (1997) open-file report. The number of samples and type of testing utilized in this study are summarized in Figure A1.

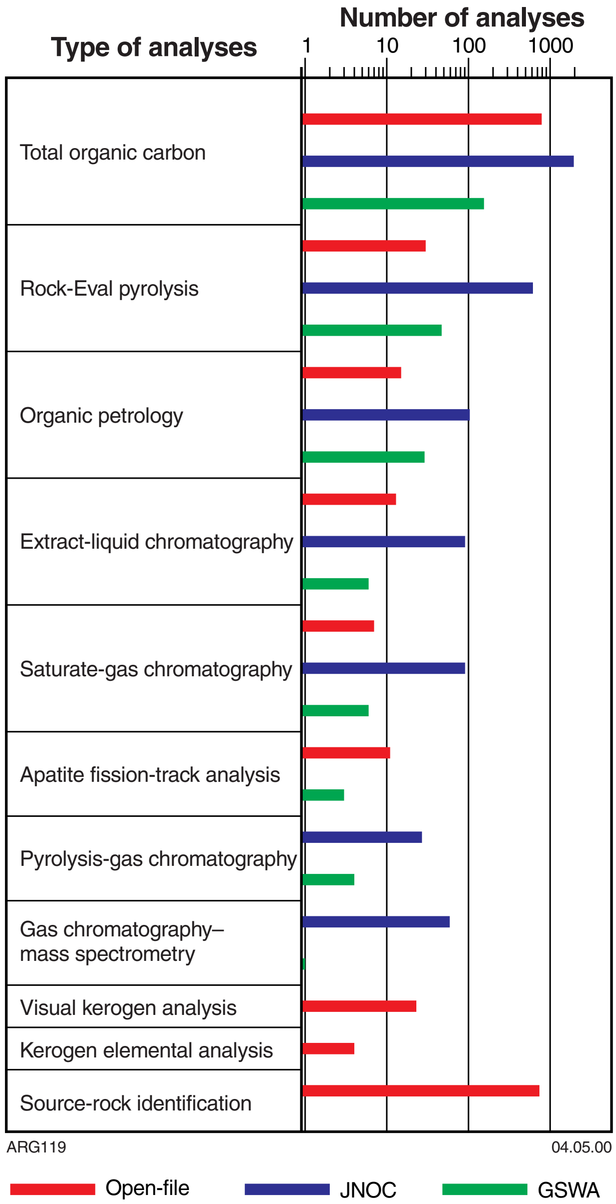

Figure A1. Type, amount, and source of the geochemical data utilized in this study

Source-rock evaluation

The petroleum-generating capacity of source rocks depends on four factors: organic richness, facies type, maturity, and expulsion efficiency. TOC content is a measure of organic richness. Rock-Eval pyrolysis quantifies the hydrocarbon-generating potential. Rock-Eval pyrolysis, pyrolysis-gas chromatography (PGC), extraction, liquid (LC) and gas chromatography (GC) identify the type of kerogen or facies. Organic petrology and T_{max} from Rock-Eval indicate thermal maturity, whereas apatite fission-track analysis (AFTA) indicates maximum palaeotemperatures and the time of cooling from these temperatures. Finally, organic maturity and timing of hydrocarbon generation from source rocks can be estimated from basin modelling. No direct method is available to measure expulsion efficiency.

Source-rock potential

Organic richness (TOC%) and potential yield ($S_1 + S_2$) from Rock-Eval pyrolysis identify source-rock intervals and indicate their hydrocarbon-generating potential. The 2896 TOC and 694 Rock-Eval values available in the database were carefully scrutinized. Most of the samples are either contaminated or so low in organic richness that their values are less than the precision limits of the analytical measurements, and they are therefore non-

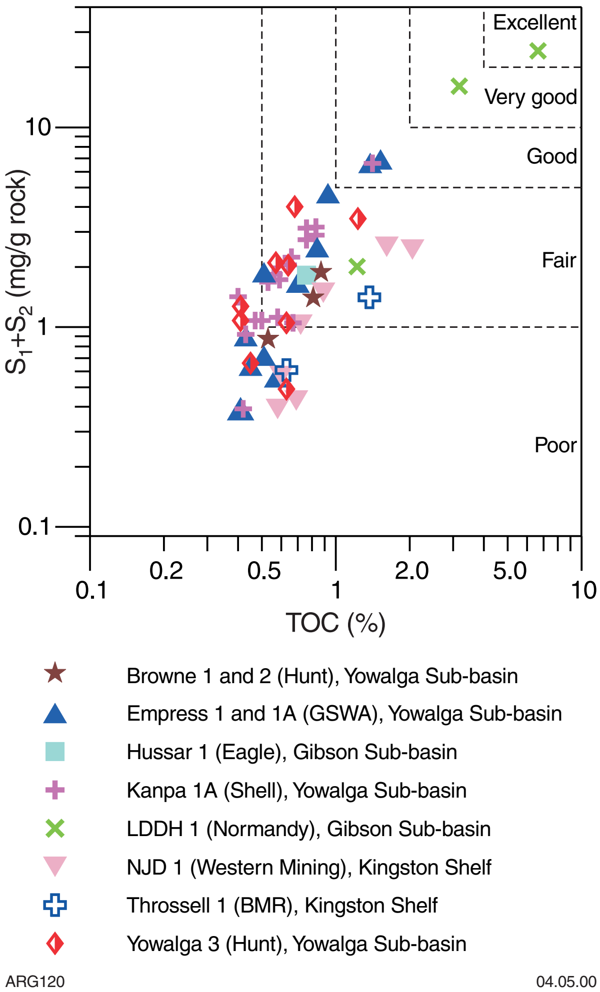

Figure A2. Petroleum-generating potential as a function of organic richness versus potential yield, for samples interpreted as reliable

source rocks. Analyses of just 53 samples were considered to be reliable enough for evaluating source-rock potential. These samples have TOC and $S_1 + S_2$ values equal to, or greater than, 0.4% and 0.4 mg/g (of rock) respectively. A plot of these samples (Fig. A2) indicates that source beds with fair to excellent generating potential are present in the following nine wells: Browne 1 and 2, Empress 1 and 1A, Hussar 1, Kanpa 1A, LDDH 1, NJD 1, Throssell 1, and Yowalga 3.

Within the Yowalga area, source beds with fair organic richness and generating potential are recognized within the Browne Formation in Browne 1 (Fig. A3).

The best source beds of the area have been recognized in Empress 1 and 1A. Beds with good organic richness and generating potential are present within the Steptoe Formation, and beds with fair source richness are present within the Kanpa Formation (Fig. A4).

Within Kanpa 1A, source beds of good organic richness and generating potential have been identified in the Browne Formation (Fig. A5). Rock-Eval parameters indicate that many of the samples from this well, which appear to have fair to good organic richness and potential yields, are in fact contaminated, and therefore they have not been highlighted in Figure A5.

Source beds of fair organic richness and generating potential are also present within the Browne and Hussar Formations in Yowalga 3 (Fig. A6). Again, many of the samples appear to be contaminated and are therefore not highlighted as source-rock intervals in Figure A6.

Source-rock type

Rock-Eval pyrolysis, pyrolysis-gas chromatography, and extract analyses were used to determine the type of kerogen in the samples. A plot of the Rock-Eval parameters of hydrogen index (HI) versus T_{max}, for the 32 samples with fair to excellent hydrocarbon-generating potential indicated that the bulk chemical character of the kerogen present is of oil- and gas-generating type II (Fig. A7).

PGC is used to evaluate the detailed molecular configuration of a kerogen in order to assess the oil- versus gas-generating potential. The PGC analyses undertaken by GSWA for four source-rock samples, three from Empress 1 and 1A and one from NJD 1, have been utilized

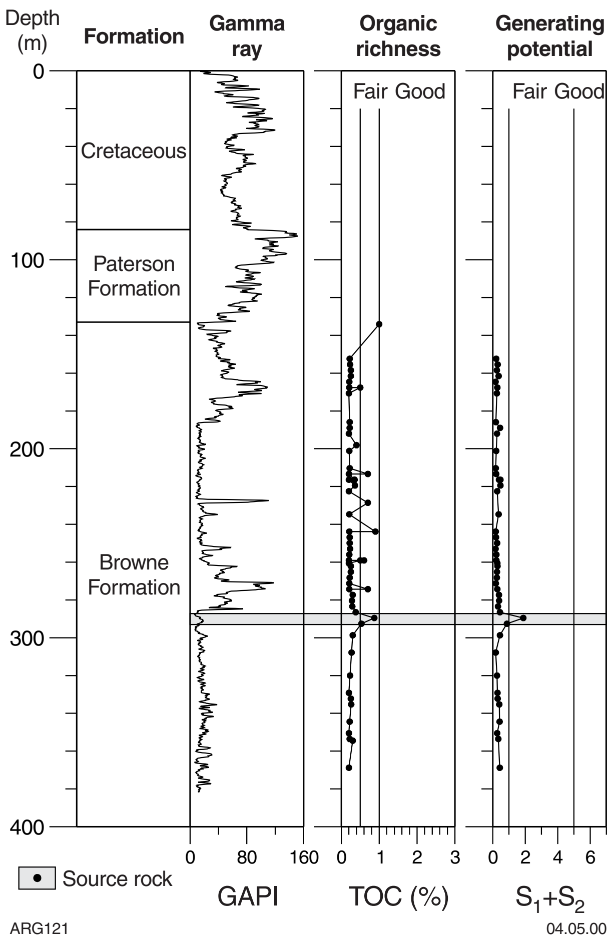

Figure A3. Organic richness and generating potential of rocks in Browne 1

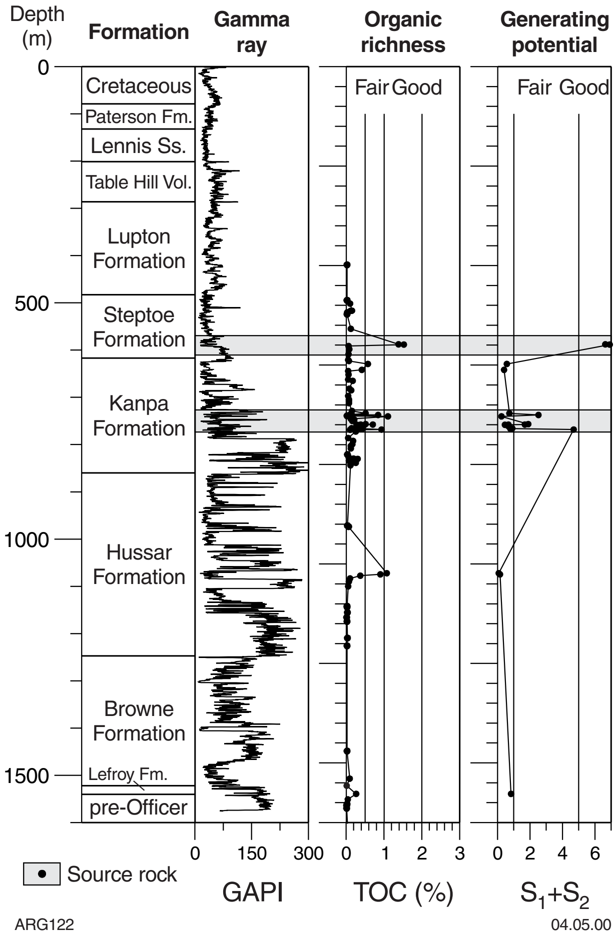

Figure A4. Organic richness and generating potential of rocks in Empress 1 and 1A

because the analytical results obtained by JNOC were not available.

The normalized compositions for the pyrolysate of these samples indicates that the concentration of hydrocarbons is high, with a predominance of aromatic hydrocarbons (Fig. A8).

The presence of a high concentration of hydrocarbons in the pyrolysate indicates that the kerogen is hydrogen rich, and hence hydrocarbon generating. However, the relative increase in aromatic compounds compared to aliphatic compounds indicates a decrease in kerogen quality, because type III kerogens have the highest relative aromatic content (Larter, 1985). The aliphatic compounds (alkanes + alkenes) in the pyrolysate are predominantly limited to 14 or less carbon atoms, thus representing mainly gasoline – kerosene hydrocarbons (Fig. A9).

The aliphatic carbon content of a kerogen, and its distribution within various structural elements, dictates the type of product likely to be generated (oil or gas) and confirms that the type of kerogen is oil and gas generating (Fig. A10).

Liquid and gas chromatography were also limited to the same samples that were tested by PGC. In Empress 1 and 1A, the high extract and hydrocarbon yields as a function of TOC content indicate that core from 588.3 m is a very good oil source-rock. The saturate-gas chromatography of this sample shows a predominance of C_{17} in the n-alkane distribution, which indicates that the organic matter is of an algal (cyanobacteria) origin (Ghori, 1999). The lower extract yields of core samples from 737.4 and 768.2 m confirms the fair source potentials suggested by the TOC contents (Ghori, 1999).

In NJD 1, the core from 327.5 m is classified as excellent – very good potential oil source-rock (Fig. A2). Due to thermal immaturity in the well, this sample yielded lower extract and hydrocarbon values as a function of TOC content, and is classified as a poor oil source-rock (Fig. A11).

The saturate-gas chromatography also indicates that the organic facies was predominantly of type II kerogen, and was deposited in a reducing environment (Fig. A12).

Gas chromatography – mass spectrometry is only available for a core sample from 327.5 m in NJD 1. The results indicate that steranes are absent (as would be expected for Neoproterozoic rocks) and that the sample is immature (Table A1).

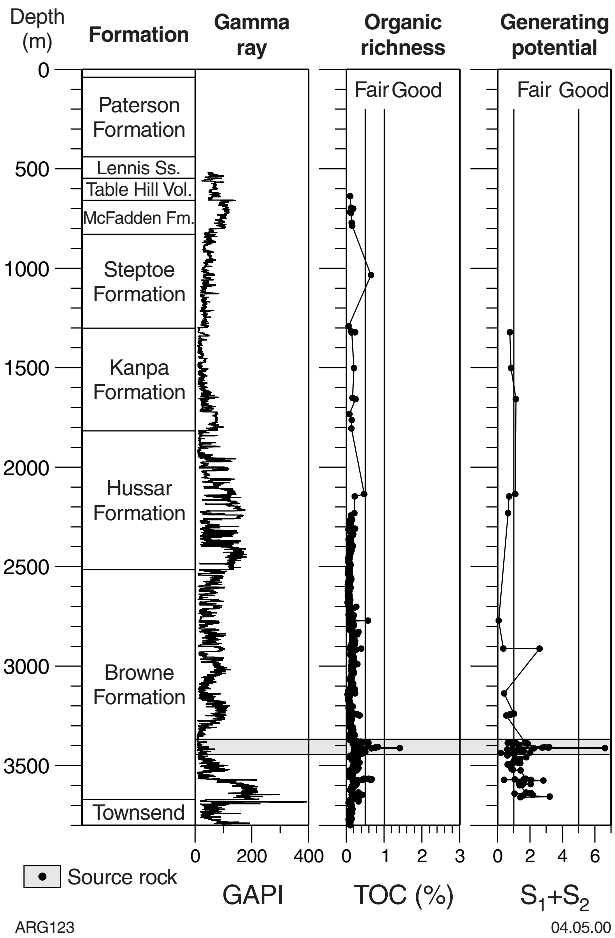

Figure A5. Organic richness and generating potential of rocks in Kanpa 1A

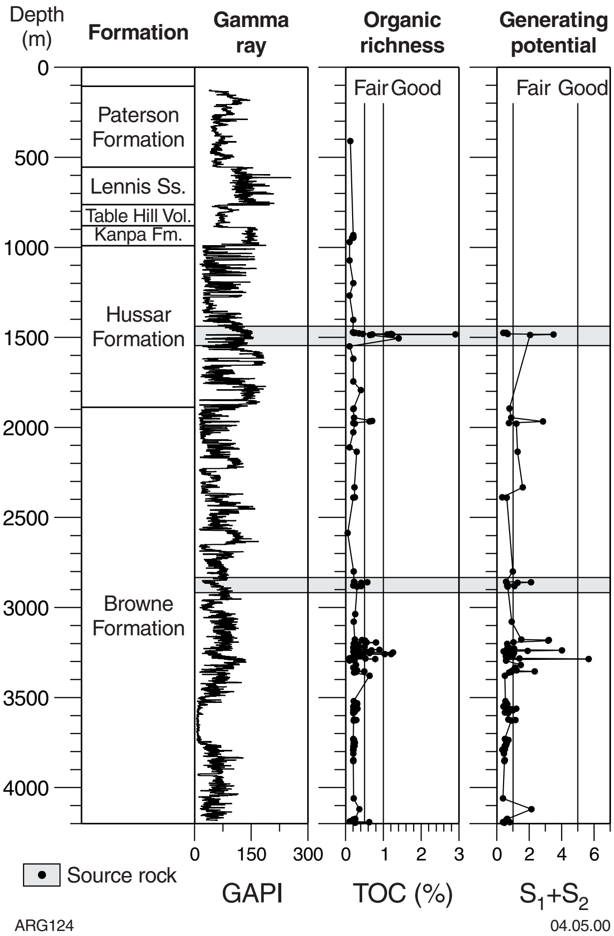

Figure A6. Organic richness and generating potential of rocks in Yowalga 3

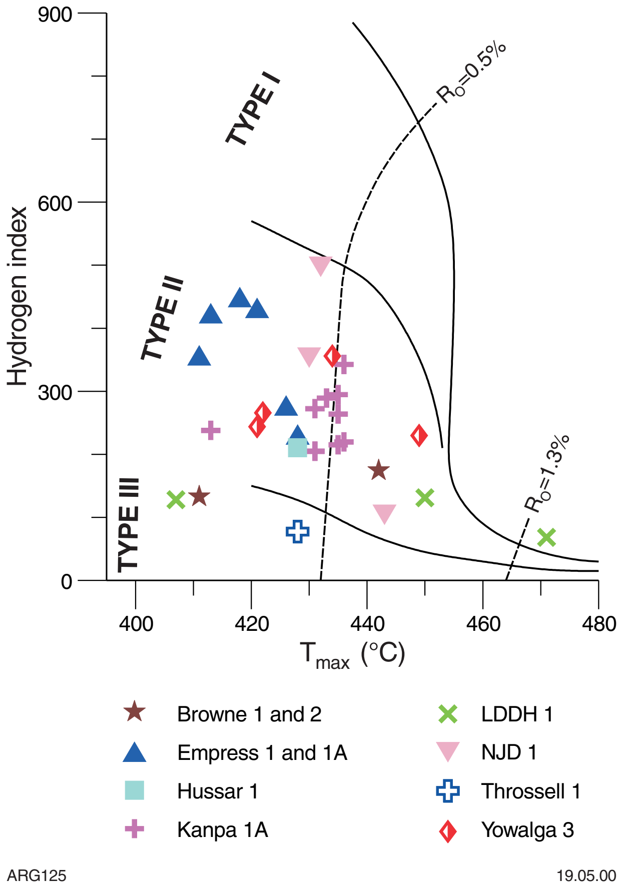

Figure A7. Type of kerogen as a function of T_{max} versus hydrogen index, from Rock-Eval pyrolysis

Organic petrology indicates that most of the organic matter consists of an alginite called lamalginite. The bulk of the lamalginite contains relatively extensive lamellae. However, smaller isolated palynomorphs are the most widely distributed form of lamalginite (Cook, 1995). These results confirm that the type II kerogen identified by the chemical analyses is of algal origin.

Source-rock maturity

Organic petrology and Rock-Eval pyrolysis have provided information on the levels of thermal maturation in the Yowalga area, as discussed below.

Organic petrology

Organic petrology for 174 samples from ten wells is available for evaluating source-rock maturity. The data provide equivalent vitrinite reflectance obtained from reflectance measurements on fluorescing and non-fluorescing lamalginite, and reservoir and thucholitic bitumen, and their fluorescence intensities have been utilized to evaluate the source-rock maturity. A plot (Fig. A13) of equivalent vitrinite reflectance versus depth suggests that most samples are within the oil window, except for the basal section within Dragoon 1, Empress 1

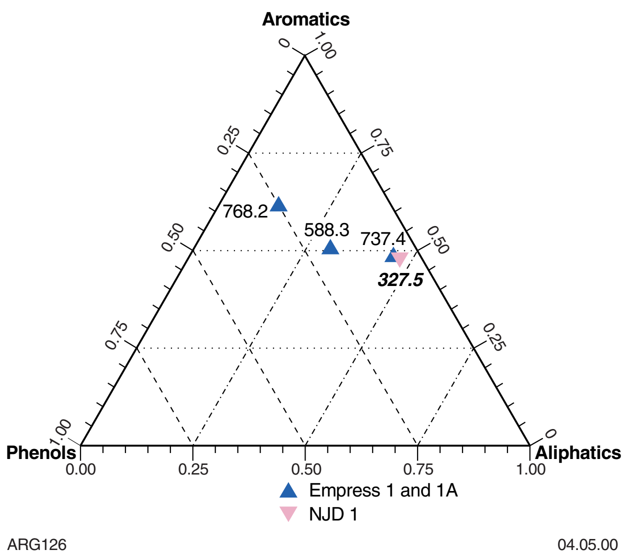

Figure A8. Normalized distribution of the aromatic, aliphatic, and phenolic compounds in the pyrolysate

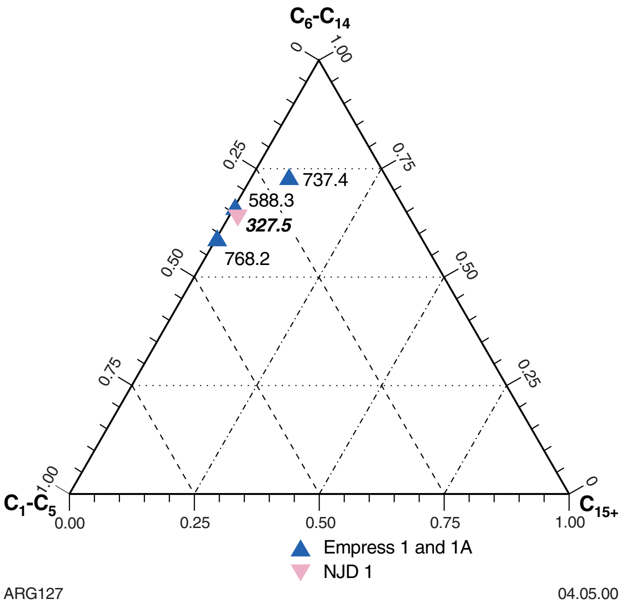

Figure A9. Normalized distribution of alkanes + alkenes in the pyrolysate

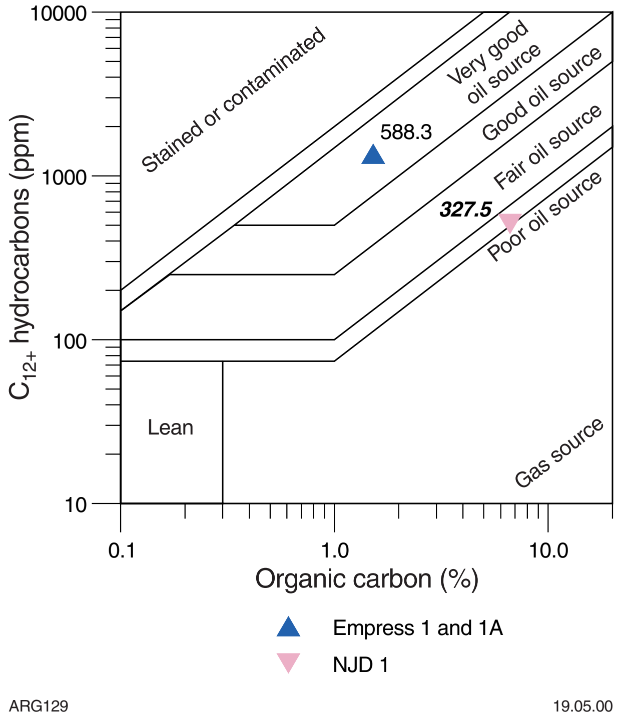

Figure A11. Source-rock rating as a function of organic richness versus C_{12+} hydrocarbon yield

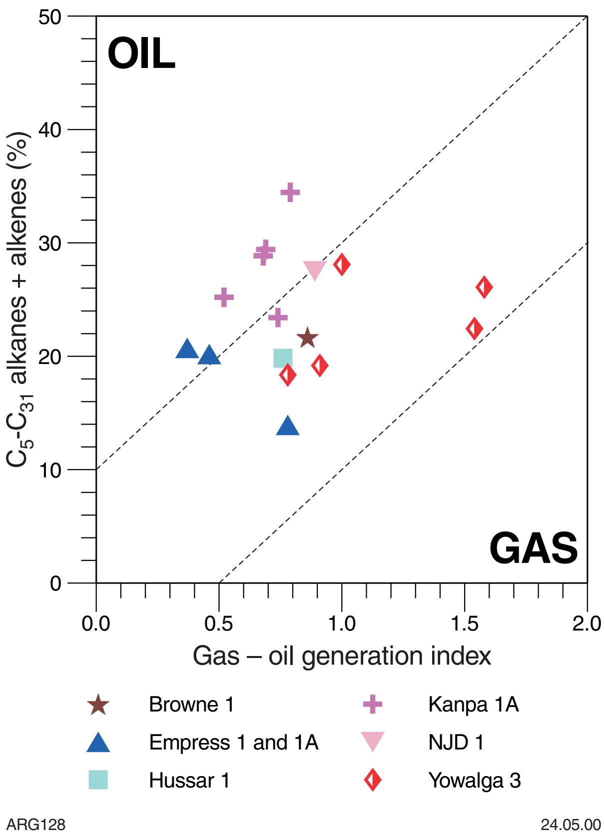

Figure A10. Oil proneness (C_5–C_{31} alkanes + alkenes) versus gas–oil generation index (C_1–C_5)/C_{6+}

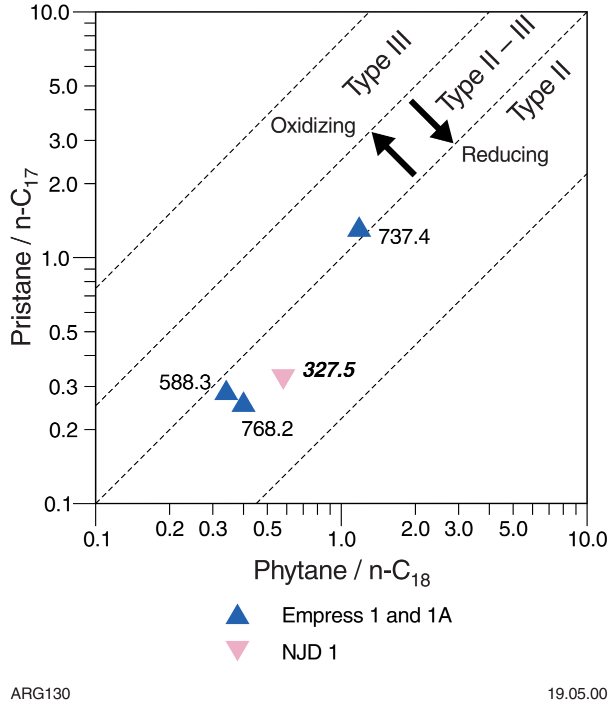

Figure A12. Kerogen type and environment of deposition as a function of pristane/n-C_{17} versus phytane/n-C_{18} ratios

Table A1. Selected parameters from gas chromatography and mass spectrometry for core 327.5 m in NJD 1

Parameter and ion	*Value*
18 a (H)-hopane/17 a (H)-hopane (Ts/Tm) 191	0.09
C_{30} hopane/C_{30} moretane 191	3.74
C_{31} 22S hopanes/C_{31} 22R hopanes 191	1.53
C_{32} 22S hopane/C_{32} 22R hopane 191	1.45
C_{15} drimane/C_{16} homodrimane 123	0.25
Rearranged drimanes/ normal drimanes 123	0.09

and 1A, LDDH 1, and Yowalga 3. Of these, Empress 1 and 1A and Yowalga 3 are within the Yowalga area. In Empress 1 and 1A, the basal section is overmature because of its pre-Officer Basin age, whereas the section in Yowalga 3 is overmature because it is deeply buried. Dragoon 1 and LDDH 1 are within the Gibson area.

Rock-Eval pyrolysis

T_{max} is the maturation parameter in °C at which the pyrolytic yield of hydrocarbons (from a rock sample) reaches its maximum. Production index (PI) is a maturation parameter that is the ratio of already generated hydrocarbon (S_1) to potential hydrocarbon (S_2). The Rock-Eval T_{max} and PI values for samples with source potential are plotted versus depth in Figure A14. The results suggest that all the samples are either immature or within the oil-generative window, except for the basal part of LDDH 1, which is located within the Gibson area. The Rock-Eval maturity parameters confirm that the Neoproterozoic rocks within the Yowalga area are not overmature for oil generation.

Source-rock thermal history

Thermal maturation modelling for four wells and six pseudowell locations from seismic sections was carried out to calculate the timing of petroleum generation and migration in the Yowalga region, utilizing the petroleum-systems modelling software of Platte River Associates. The modelling was performed in three steps: (i) one-dimensional modelling of a single well location, utilizing version 7.06 of BasinMod 1-D; (ii) one-dimensional modelling of multi-well locations, using version 7.06 of BasinView; and (iii) two-dimensional modelling of a cross section using version 4.13 of BasinMod 2-D.

In the first step, one-dimensional burial histories were reconstructed from the stratigraphic sections and their lithologies as encountered in the wells, and were estimated for pseudowells from the seismic sections. The thermal histories were reconstructed using estimated erosion histories and by adjusting thermal conductivities and transient heat flow to constrain maturity models versus measured data. Corrected bottomhole temperatures, equivalent vitrinite reflectance (%Ro), T_{max}, and information from AFTA were used to constrain present-day temperatures and palaeotemperatures. Time-stratigraphy utilized in developing the models is summarized in Table A1. A 1% content of type II kerogen is assumed for

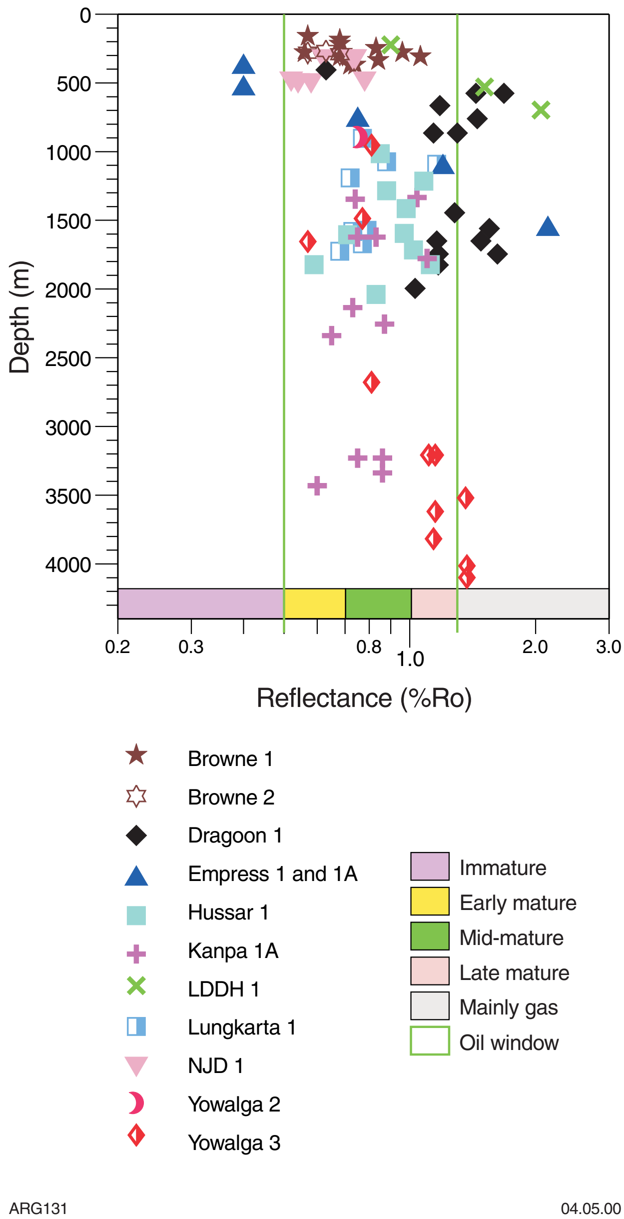

Figure A13. Maturity as a function of equivalent vitrinite reflectance versus depth

rocks in the kinetic modelling of source-rock maturation and petroleum generation as a function of geothermal history. The following vitrinite reflectance values have been adopted to define maturation stages: immature (<0.5% Ro), early mature (0.5 – 0.7% Ro), mid-mature (0.7 – 1.0% Ro), late mature (1.0 – 1.3% Ro), and main gas generation (>1.3% Ro).

Maturity calibration and burial histories for three key wells are illustrated in Figure A15. The T_{max} values are consistently lower than the equivalent vitrinite reflectance values in this area. For this study, the deepest equivalent vitrinite reflectance value is considered to represent the maximum maturity attained in the well. The modelling suggests that the Kanpa Formation at K2, and deeper older formations in Empress 1 and 1A, Kanpa 1A, Yowalga 3,

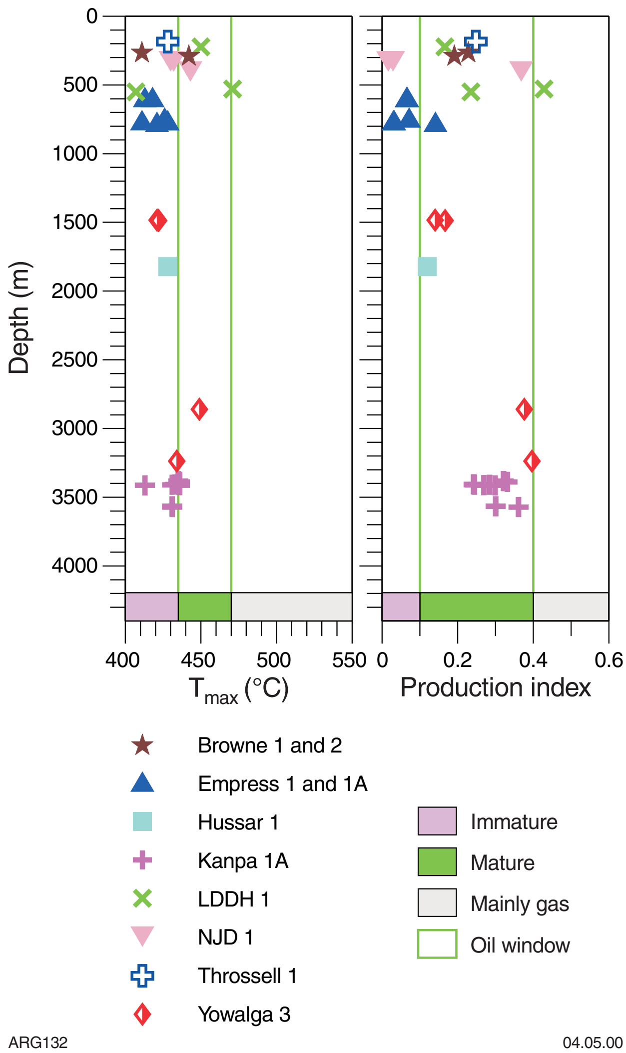

Figure A14. Maturity as a function of the Rock-Eval parameters, T_{max} and production index, versus depth

and the Hussar Formation at H4 are all within the mature zone for oil and gas generation.

In the second step, one-dimensional models developed in the first step were used to develop a multi-well model. The purpose of this was to estimate geographic variation in the present-day maturation levels at the surface of those stratigraphic intervals within which source beds have been identified in the study area. Source beds have been identified within the S1 interval of the Steptoe Formation and K1 interval of the Kanpa Formation in Empress 1 and 1A; in the H3 interval of the Hussar Formation and B4 interval of the Browne Formation in Yowalga 3; and in the B2 interval of the Browne Formation in Kanpa 1A. Figure 16 illustrates the maturation levels at the surface of the source-rock horizons, based on the ten one-dimensional models. The modelling suggests that the Steptoe Formation at the S1 level is immature in most of the area, except in the northernmost part (Fig. A16a). The K1 interval of the Kanpa Formation is early mature in some parts of the area, as shown in Figure A16b. The maturity level progressively increases from early to overmature in the deeper intervals, and it is higher in the northern part of the study area. Figures A16c–e illustrate the maturity levels of the H3 interval of the Hussar Formation, and the B4 and B2 intervals of the Browne Formation respectively.

In the final step, two-dimensional modelling of a composite cross section from Empress 1 and 1A in the south to the pseudowell at SP 2030 on seismic line T80-11 in the north was carried out. The locations of the wells are shown in Figure A16. The aim was to estimate and illustrate the maturation levels across the region and to determine the timing of hydrocarbon generation. Firstly, the model was constrained against measured present-day temperatures and maturity (Fig. A17), and then the maturation levels were calculated using lateral variation in present-day temperatures and palaeo-temperatures. The estimated maturation stages reached at different stratigraphic levels across the area are illustrated in Figure A18.

Kinetic modelling of petroleum generation as a function of geothermal history, and type and amount of kerogen was used to determine the timing of hydrocarbon generation, using a 1% content of type II kerogen. Figure A19 illustrates the timing as a function of hydrocarbon-generation rate for three horizons that have attained enough maturity to begin hydrocarbon generation in three key wells. In this figure, a constant scale for the hydrocarbon-generation rate is used to compare the level of generation reached in different wells.

The B4 horizon in Empress 1 and 1A is the most mature source rock in the modelled wells, and the maximum rate of hydrocarbon generation was reached during the Neoproterozoic. In Kanpa 1A and Yowalga 3, the older and deeper B2 interval is less mature and at an early stage of hydrocarbon generation. However, this early stage of oil generation was reached during the Neoproterozoic. Source beds containing the intervals H3, K1, and S1 are at the earliest stages of oil and gas generation in these wells.

The modelling suggests that the highest maturity was reached in the northern part of the area, and therefore the pseudowell at SP 2030 on seismic line T80-11 is used to illustrate the timing of hydrocarbon generation for the five intervals most likely to contain source rocks. In Figure A20, different scales for hydrocarbon-generation rate are used for the Browne, Hussar, Kanpa, and Steptoe Formations because their generation rate can not be demonstrated on the same scale due to vast differences in their rates of generation.

The modelling clearly demonstrates the vast differences in timing and levels of hydrocarbon generation attained in the Browne, Hussar, Kanpa, and Steptoe Formations. The hydrocarbon-generative history of the area was affected by its burial and erosional histories. There are at least seven regional unconformities in the area (Table A2). The Browne Formation was deeply buried, and reached optimum maturity for hydrocarbon generation during the early evolution of the basin, and consequently most of its generative potential was exhausted during the Neoproterozoic. Whereas the Hussar, Kanpa, and Steptoe Formations were not buried deeply enough to have

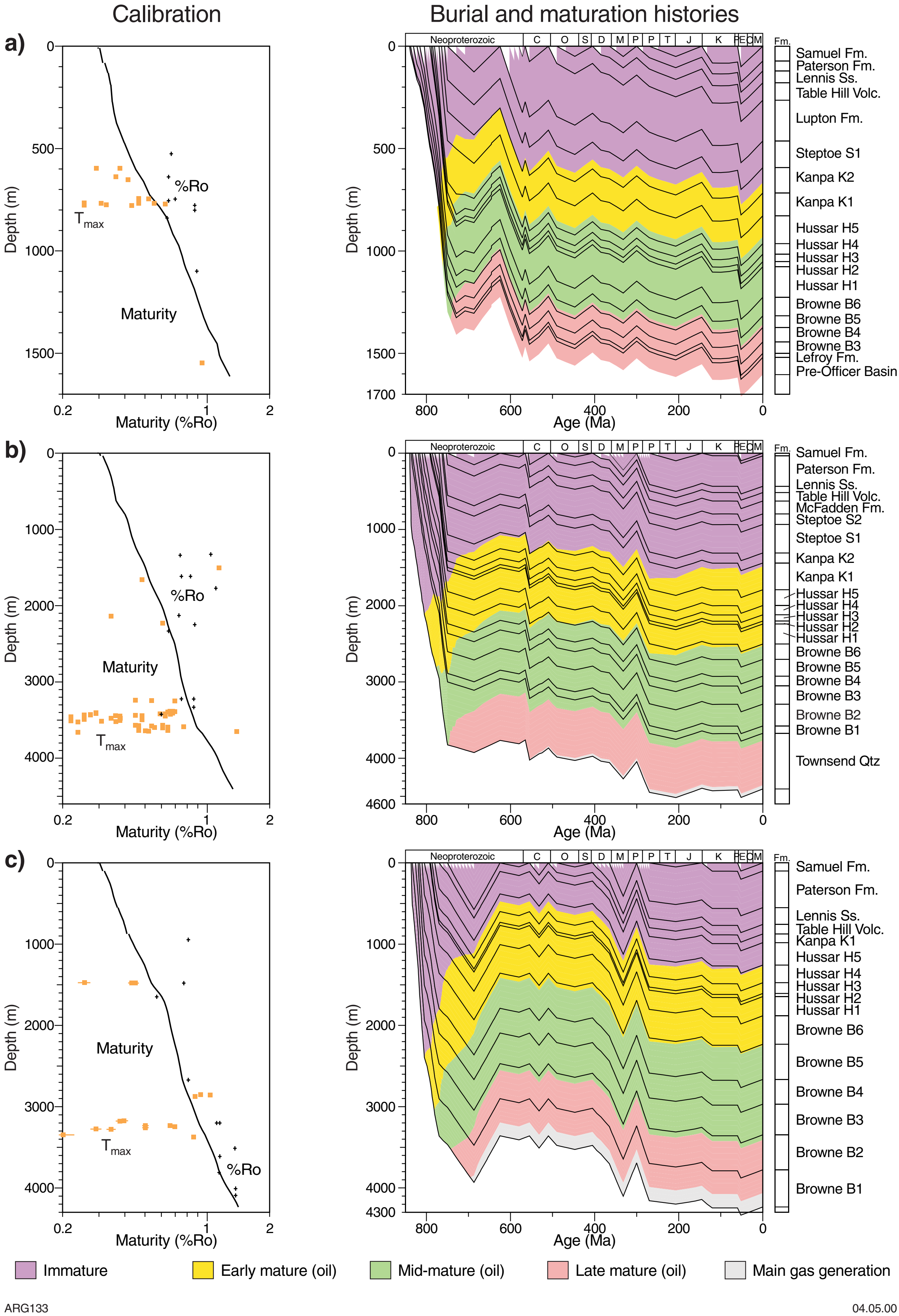

Figure A15. Calibration of calculated versus measured maturity, and burial and thermal history of three key wells: a) Empress 1/1A; b) Kanpa 1A; c) Yowalga 3

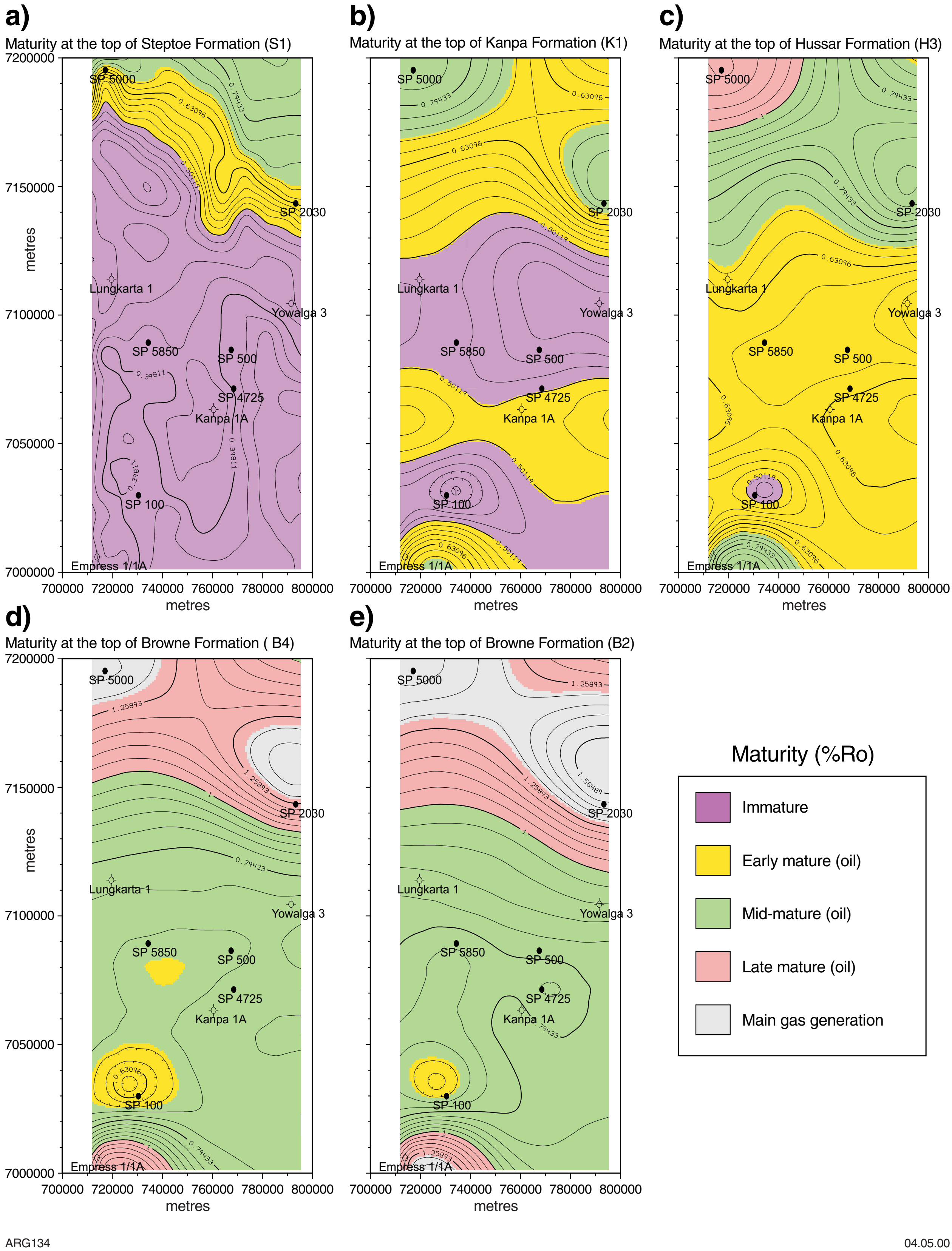

Figure A16. Maturity at the surface of the five key stratigraphic horizons: a) S1 of the Steptoe Formation; b) K1 of the Kanpa Formation; c) H3 of the Hussar Formation; d) B4 of the Browne Formation; e) B2 of the Browne Formation

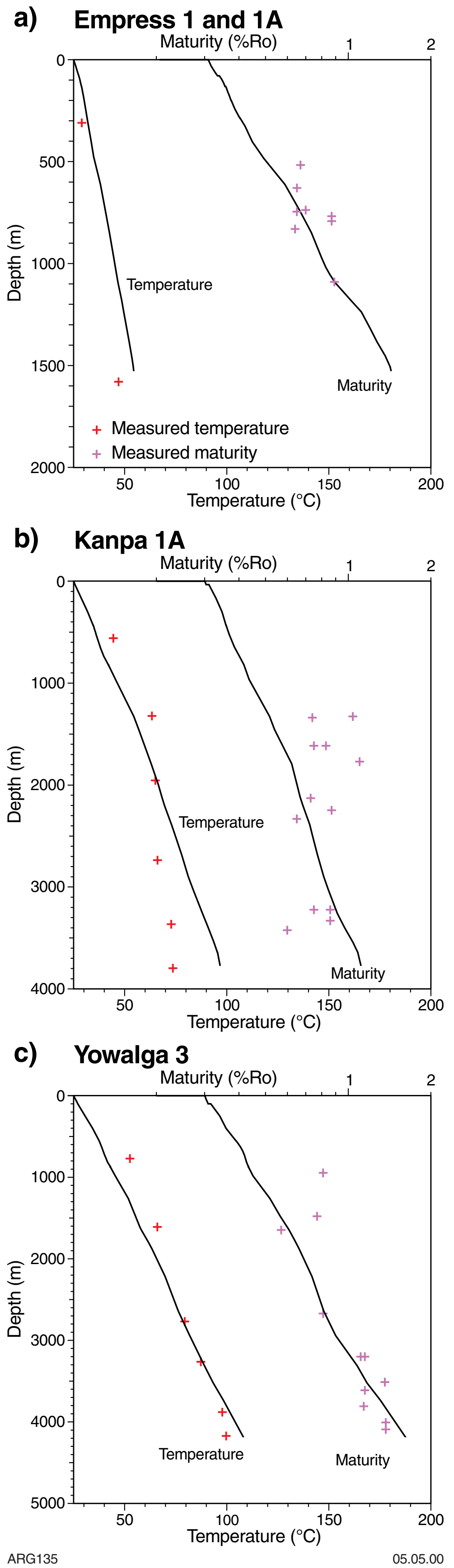

Figure A17. Calibration of calculated versus measured present-day maturity: a) Empress 1/1A; b) Kanpa 1A; c) Yowalga 3

reached optimum maturity, and their hydrocarbon-generative potential was not exhausted during the Neoproterozoic. Therefore, the timing of hydrocarbon generation as function of source-rock maturation due to burial and time is spread throughout the geological history of the basin's evolution (Fig. A20).

Conclusions

The available geochemical data for 1307 samples (TOC and Rock-Eval pyrolysis) indicate that only 53 samples are reliable for the evaluation of source-rock potential. These 53 samples identify thin source beds with fair to excellent generating potential in Browne 1 and 2, Empress 1 and 1A, Hussar 1, Kanpa 1A, LDDH 1, NJD 1, Throssell 1, and Yowalga 3. The organic-rich source beds are present within the B2 and B4 intervals of the Browne Formation, the H3 interval of the Hussar Formation, the K1 interval of the Kanpa Formation, and the S1 interval of the Steptoe Formation. Pyrolysis-gas chromatography and extract analyses indicate that most the organic matter within the source beds is type II kerogen.

The organic petrology and Rock-Eval pyrolysis analyses indicate that the measured maturity of the Neoproterozoic succession ranges from immature to overmature. However, a significantly thick Neoproterozoic succession is presently within the oil window in the studied wells.

The hydrocarbon-generation modelling suggests that the optimum maturity for a maximum rate of hydrocarbon generation within the Browne Formation was reached at an early stage in the basin's evolution, and most of the hydrocarbon-generative potential was exhausted during the Neoproterozoic. However, the Hussar, Kanpa, and Steptoe Formations were not buried deeply enough to have reached optimum maturity, and their hydrocarbon-generative potential was not exhausted during the Neoproterozoic. Therefore, the timing of hydrocarbon generation as a function of source-rock maturation due to burial temperature and time is spread throughout the geological history of the basin's evolution.

The presence of thin beds with excellent to fair oil-generating potential indicates the development of organic-rich facies, whereas the presence of minor oil and numerous bitumen shows indicates the existence of a petroleum system within the Neoproterozoic rocks of the western Officer Basin.

The vast area covered by the Yowalga region of the western Officer Basin is very poorly explored, and the sparse well control precludes a complete assessment of the source-rock potential for the Neoproterozoic successions. Effective source-rock units and a commercially viable petroleum system can not be identified from the available dataset. However, thin, good quality source rocks have been verified in the Browne, Hussar, Kanpa, and Steptoe Formations, and it has been established that a significant part of the Neoproterozoic section is presently within the oil window.

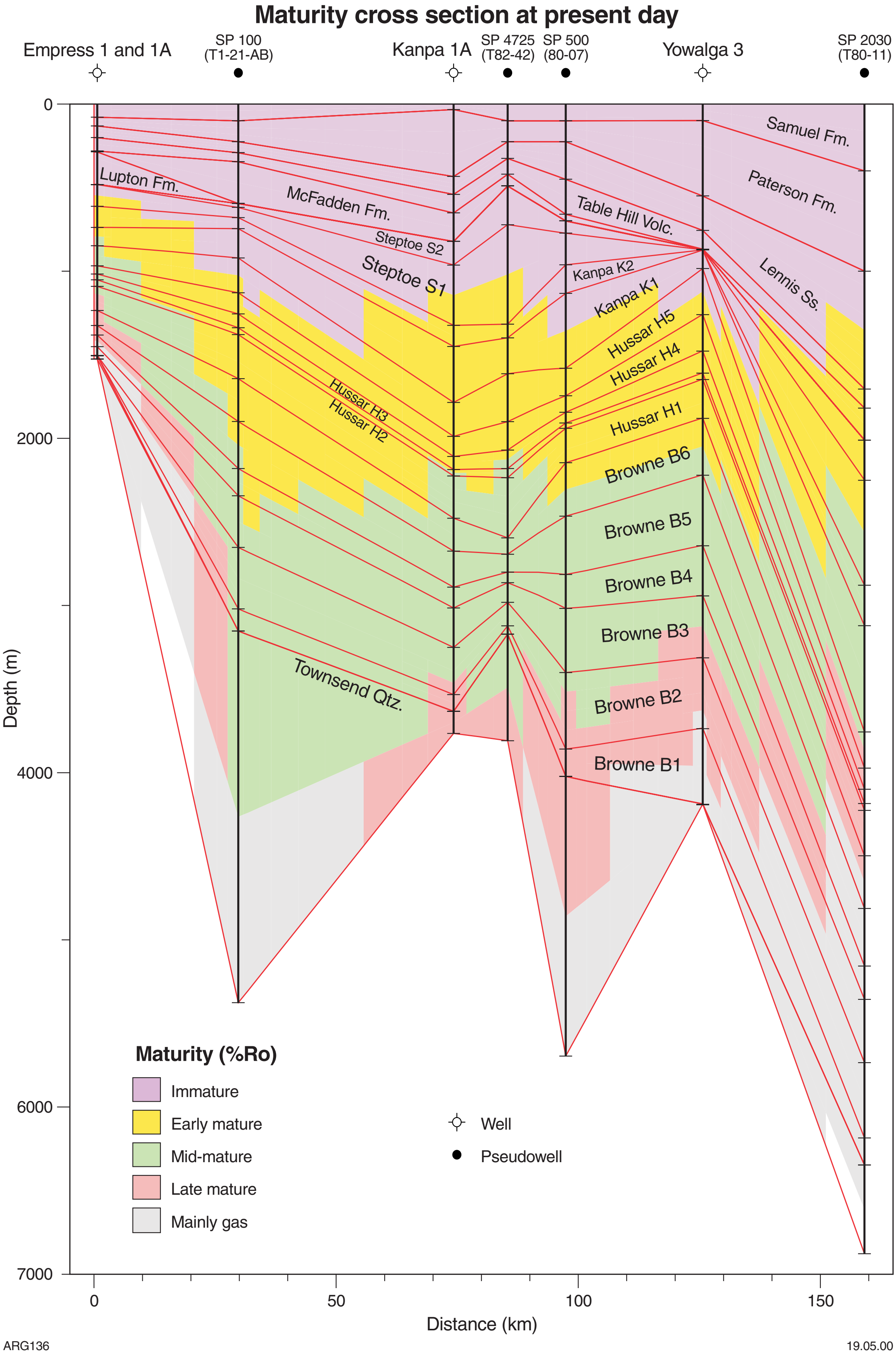

Figure A18. Maturity across the Yowalga area, from Empress 1 and 1A in the south to SP 2030 on seismic line T80-11 in the north. The maturity is based on two-dimensional modelling, and well locations are shown in Figure 16

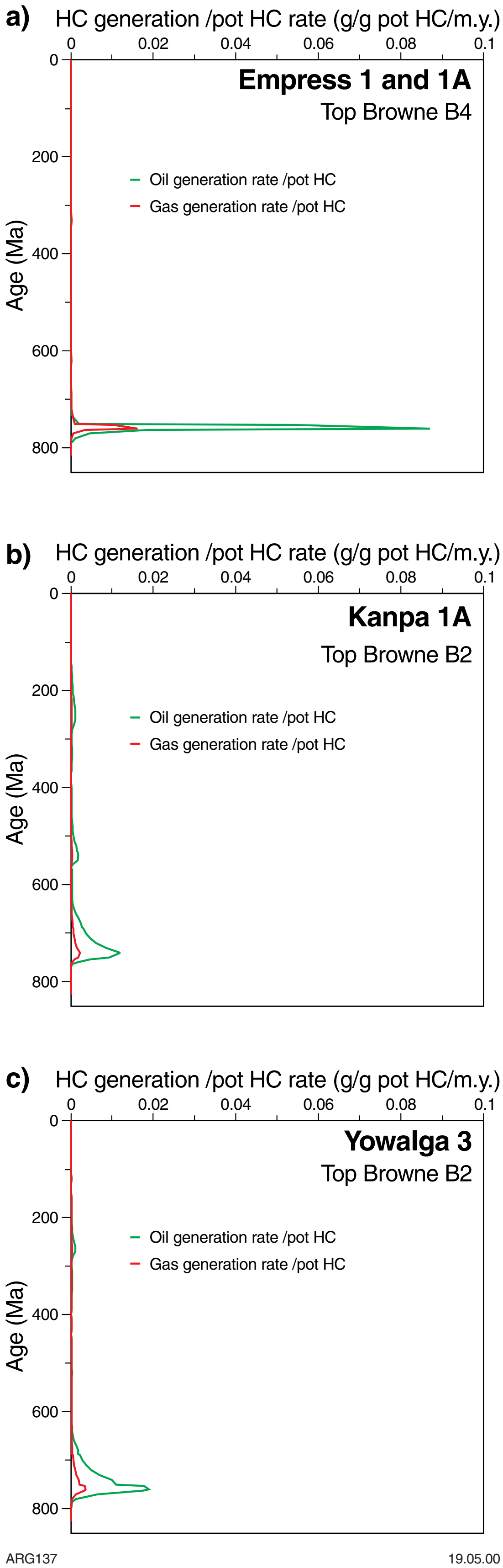

Figure A19. Rate of hydrocarbon generation versus time for the Browne Formation: a) Top B4 horizon in Empress 1 and 1A; b) Top B2 horizon in Kanpa 1A; Top B2 horizon in Yowalga 3

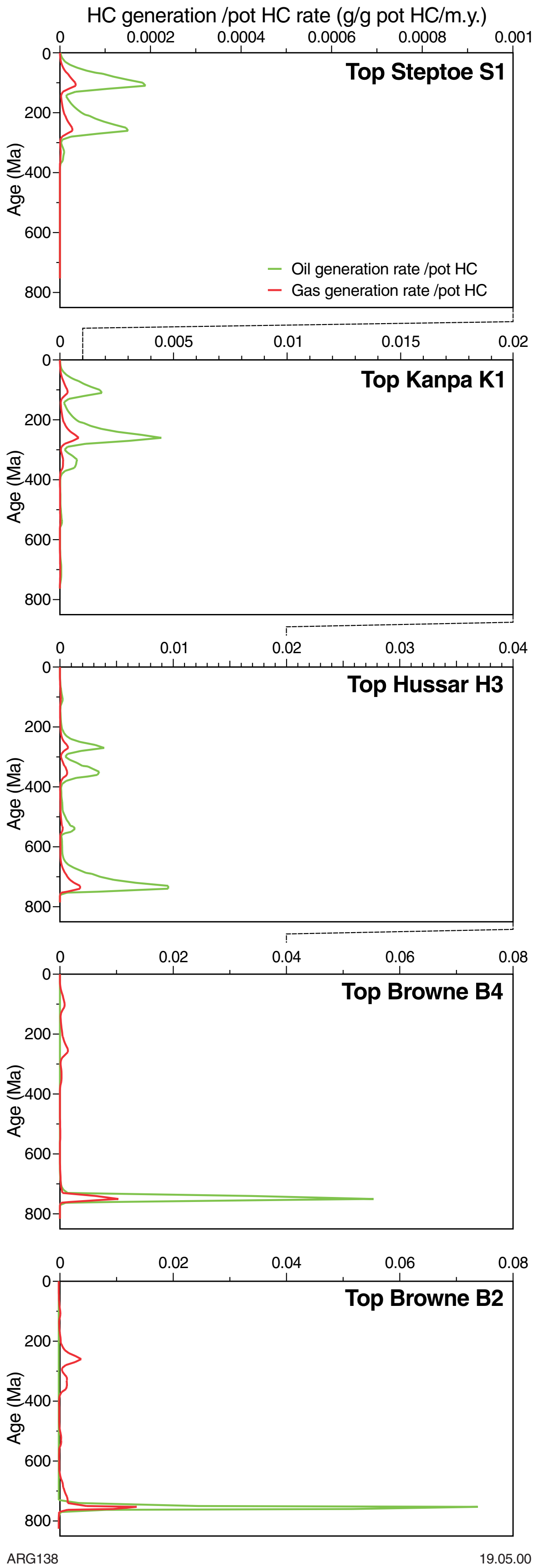

Figure A20. Rate of hydrocarbon generation at SP 2030 on seismic line T80-11 for the top of the S1, K1, H3, B4, B2 horizons of the Steptoe, Kanpa, Hussar, and Browne Formations respectively

Table A2. Time-stratigraphy used in the maturity models

Formation	*Base age (m.y.)*	*Empress 1/1A*	*Kanpa 1A*	*Yowalga 3*	*Lungkarta 1*	*SP 100 (81-21-AB)*	*SP 4725 (T82-42)*	*SP 500 (80-07)*	*SP 5850 (81-11-E)*	*SP 2030 (T80-11)*	*SP 5000 (T81-29)*
					metres						
	120			Cenozoic unconformity							
Samuel Fm.	145	0	0	0	0	0	0	0	0	0	0
	270			Mesozoic unconformity							
Paterson Fm.	300	79	40	106	88	100	100	100	100	400	30
	365	–	–	Alice Springs Orogeny unconformity							
Lennis Ss.	405	131	440	555	364	225	225	225	225	1 000	430
	490	–	–	Rodingan Movement unconformity							
Table Hill Volc.	510	201	547	763	540	291	325	650	454	1 705	759
	555	–	–	Delamerian Orogeny unconformity							
McFadden Fm.	565	–	658	–	704	345	346	659	517	1 819	944
	580	–	–	Petermann Ranges Orogeny unconformity							
Lupton Fm.	625	286	–	_	_	_	_	_	_	_	_
	750	–		Areyonga Movement unconformity							
Steptoe S2	753	–	829	_	_	595	490	699	658	2 011	1 842
Steptoe S1	760	483	970	_	_	618	722	772	821	2 251	2 051
Kanpa K2	763	617	1 341	_	809	679	1 333	964	1 250	2 881	2 600
Kanpa K1	770	748	1 472	880	859	746	1 417	1 138	1 351	3 123	2 944
Hussar H5	780	860	1 817	991	1 196	924	1 638	1 597	1 617	3 759	3 850
Hussar H4	786	981	2 020	1 267	1 400	1 137	1 926	1 763	1 830	3 975	3 937
Hussar H3	790	1 030	2 140	1 485	1 578	1 264	2 096	1 861	1 956	4 102	3 989
Hussar H2	792	1 065	2 220	1 617	1 682	1 348	2 209	1 927	2 040	4 187	4 023
Hussar H1	805	1 105	2 259	1 655	1 722	1 389	2 264	1 959	2 081	4 228	4 040
Browne B6	810	1 250	2 515	1 888	_	1 658	2 627	2 168	2 350	4 500	4 150
Browne B5	816	1 340	2 712	2 228	_	1 915	2 725	2 488	2 559	4 815	4 296
Browne B4	820	1 397	2 927	2 650	_	2 196	2 832	2 837	2 787	5 159	4 454
Browne B3	826	1 466	3 052	2 950	_	2 359	2 895	3 040	2 920	5 359	4 547
Browne B2	834	–	3 288	3 320	_	2 668	3 012	3 423	3 170	5 737	4 721
Browne B1	836	–	3 570	3 744	_	3 036	3 153	3 881	3 469	6 188	4 929
Lefroy Fm	838	1 521	–	_	_	_	_	_	_	_	_
Townsend Qtze	840	–	3 671	_	_	3 168	3 203	4 045	3 576	6 350	5 004
Pre-Officer	_	1 540	–	_	_	_	_	_	_	_	_
TD	_	1 624	3 803	4 197	1 770	5 391	3 840	5 718	5 738	6 880	6 105

NOTE:

m.y.	million years
Fm.	Formation
Ss.	Sandstone
Volc.	Volcanics
Qtze	Quartzite
TD	total depth

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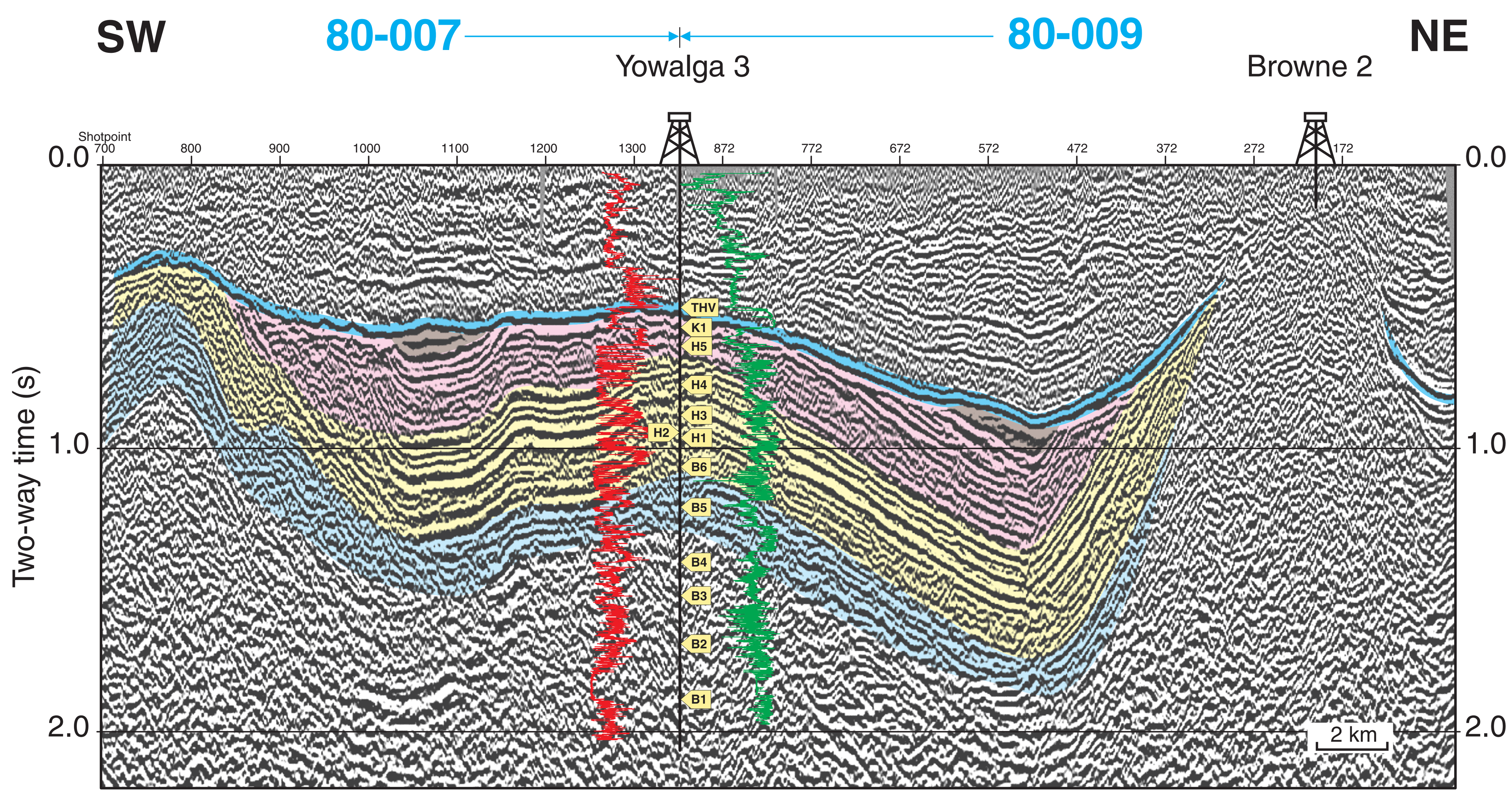


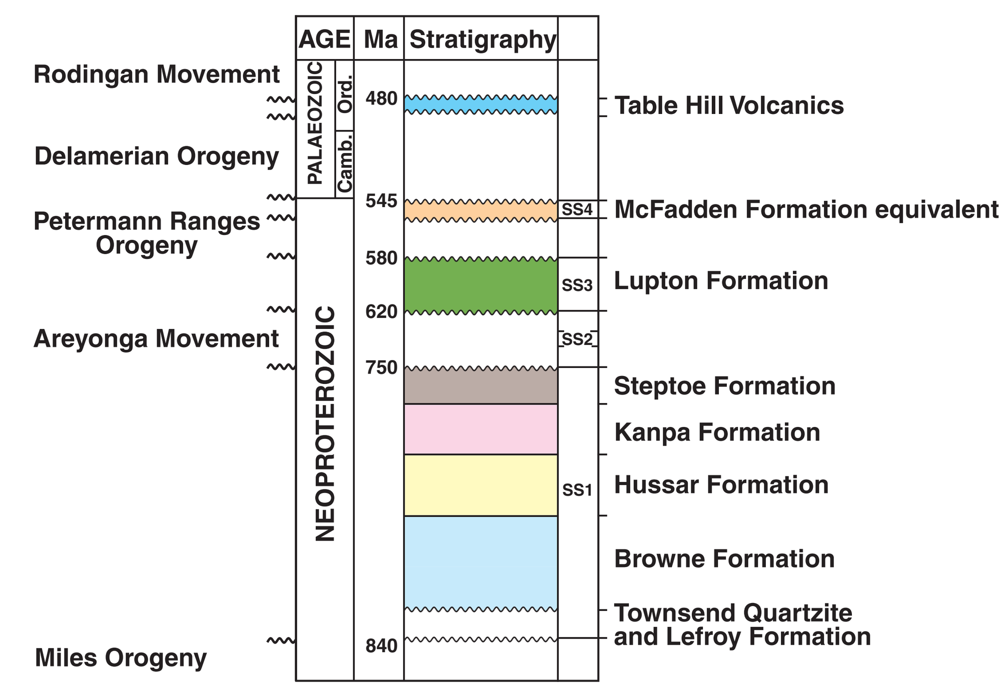
REFERENCE

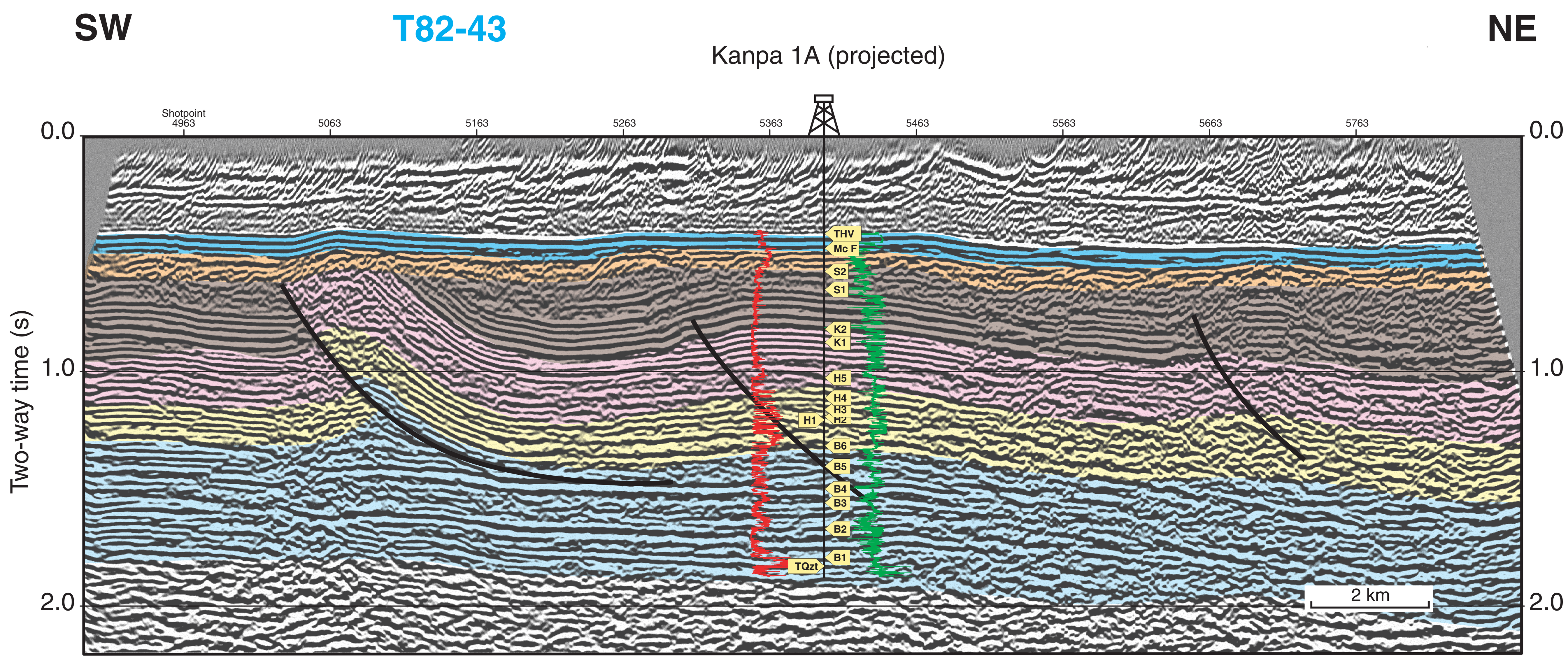
- Gamma-ray log (API) increasing →
- Sonic log (sec/ft) increasing ←
- SS Supersequence

Seismic horizons:

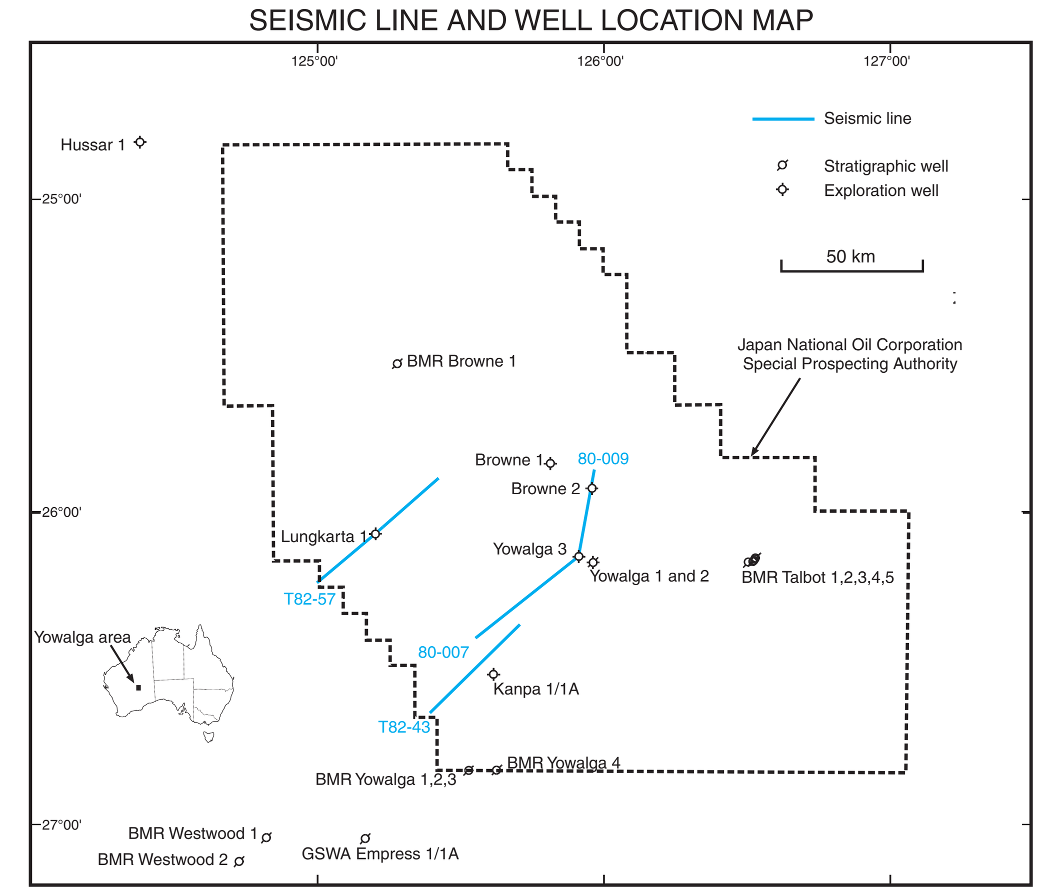
- THV Table Hill Volcanics
- McF McFadden Formation equivalent
- S Steptoe Formation
- K Kanpa Formation
- H Hussar Formation
- B Browne Formation
- TQzt Townsend Quartzite

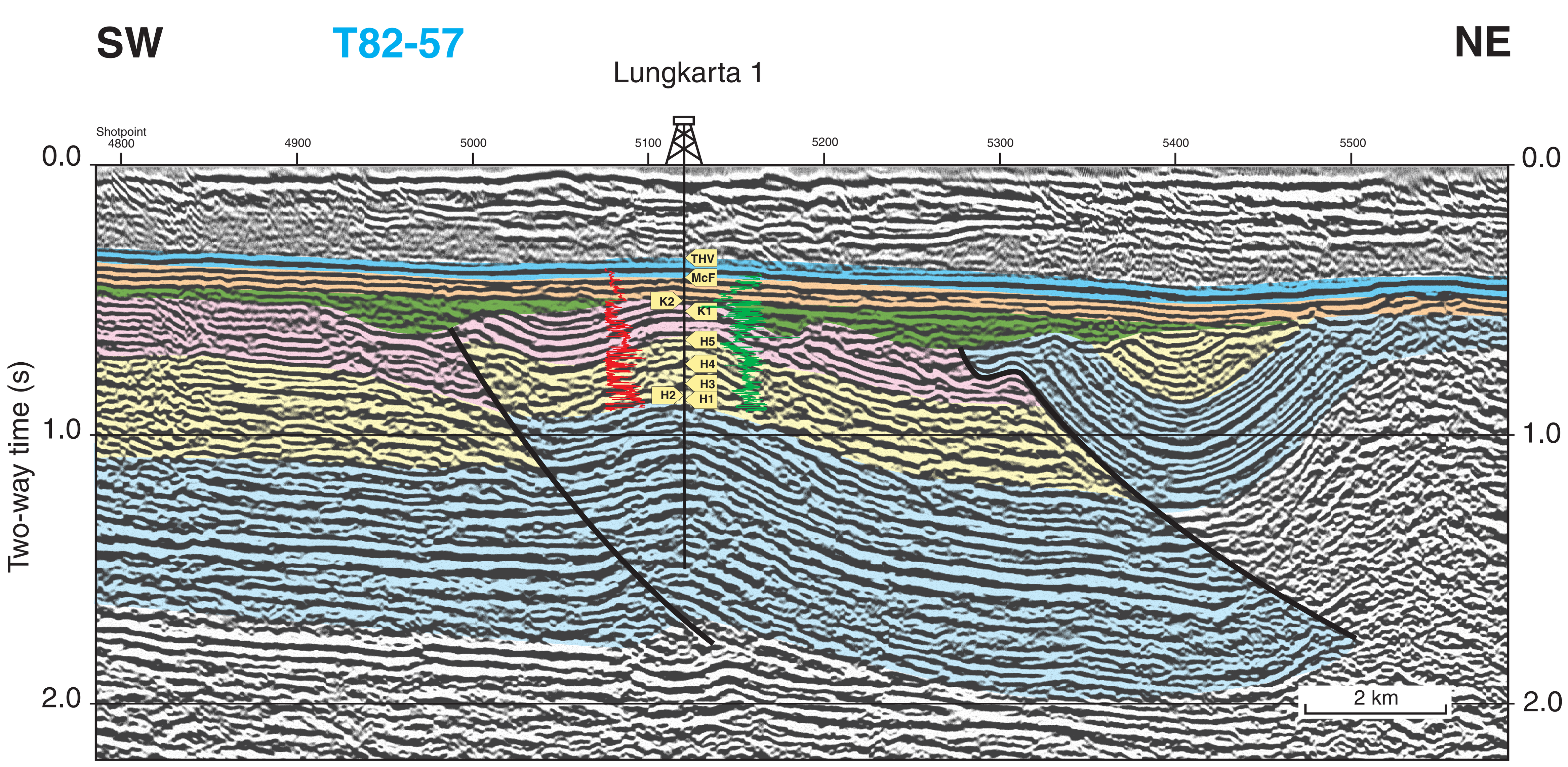
LEGEND





SEISMIC LINE AND WELL LOCATION MAP





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Edited by G. Loan and L. Day
Drafted by M. C. Jones

CAD file: NA94 (24.5.00)

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Printed by the Sands Print Group, Western Australia

The recommended reference for this plate is:
Apak, S. N., and Moors, H. T., 2000, Composite seismic montage, Yowalga area, Officer Basin, *in* Basin development and petroleum exploration potential of the Yowalga area, Officer Basin, Western Australia *by* S. N. Apak and H. T. Moors: Western Australia Geological Survey, Report 76, Plate 1

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GEOLOGICAL SURVEY OF WESTERN AUSTRALIA
REPORT 76 PLATE 1

COMPOSITE SEISMIC MONTAGE
YOWALGA AREA, OFFICER BASIN