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# Preliminary Evaluation of the Petroleum Potential of Australia's Central Eastern Margin

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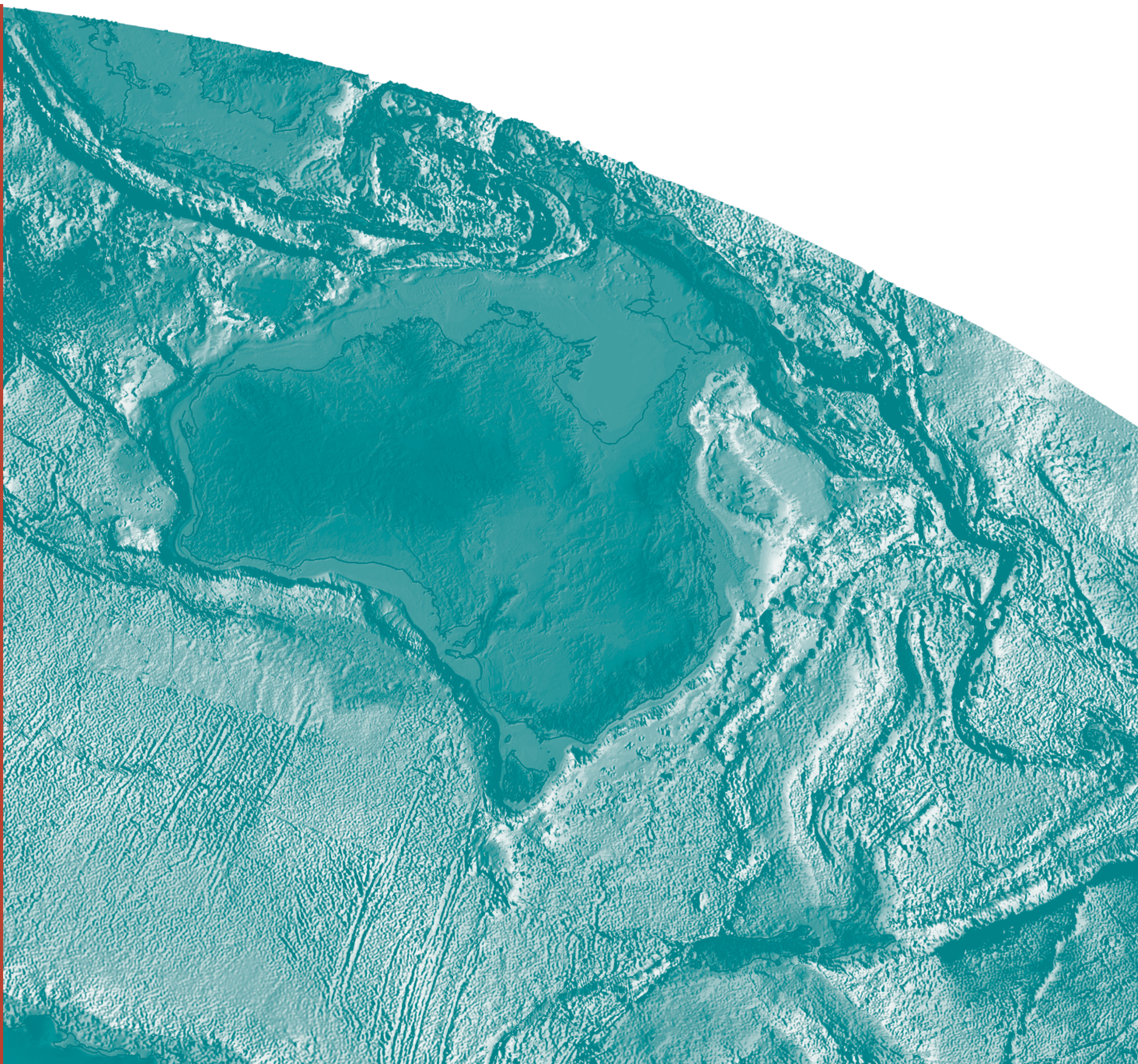

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GEOSCIENCE AUSTRALIA
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**Geoscience Australia Record 2004/06**

# Preliminary Evaluation of the Petroleum Potential of Australia's Central Eastern Margin.

**A.E. Stephenson and G.J. Burch**

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# Executive Summary

Australia's east coast north of Bass Strait has been very sparsely explored for petroleum. Exploration permits have been intermittently held over the offshore Sydney Basin, including an active permit at the time of writing, and some permits were held in north Queensland waters in the 1960s and 1970s, but much of the geology of this eastern continental margin is virtually unknown. This report provides a preliminary assessment of the petroleum potential of Australia's east coast, from the border between New South Wales and Victoria in the south, to the southern boundary of the Great Barrier Reef Marine Park (GBRMP) offshore southeast Queensland in the north. Petroleum exploration is prohibited within the GBRMP, and no assessment of this area is included in the report.

Palaeozoic basement rocks covered by a veneer of Cainozoic sediments underlie a large part of the study area (Figure 1). At least four sedimentary basins also underlie the continental shelf and probably the continental slope in the case of the Sydney and Maryborough Basins. These two basins are also the best known; but the Clarence-Moreton and Nambour Basins are also known to have offshore extensions on the shelf. It is also possible but not certain that the Ipswich and Lorne Basins could have offshore components, and there is some evidence of a pre-Clarence-Moreton Basin sedimentary sequence offshore of the Coffs Harbour area. In addition to these basins, several graben and half-graben associated with Tasman Sea rifting may occur within basement dominated shelf and slope areas - two of these features are known from very limited data.

We make the following preliminary assessments of the central east coast offshore basins.

The offshore **Sydney Basin** contains at least 6,000 m of Permian to Triassic marine and non-marine sequences unconformably overlying Palaeozoic economic basement. Whereas the onset of Sydney Basin deposition was perhaps triggered by rifting, deposition was largely driven by foreland thrust loading initially directed from the east and later from the north and northeast. Marine sequences dominated in the Early Permian; fluvial deposition commenced in the late Early Permian and dominated thereafter. Towards the top of these cycles thick coal measure facies were deposited, particularly in the Late Permian. The post-Triassic history of the Sydney Basin is largely unconstrained because subsequent uplift and erosion removed younger sediments, but it is generally agreed that it experienced on-going deposition and subsidence during the Jurassic, prior to a stabilisation and possibly minor erosion, throughout the Early Cretaceous. Subsequently, the Sydney Basin experienced rapid uplift and extensive erosion as seafloor spreading began in the Tasman Sea.

Whilst the Sydney Basin is considered gas-prone numerous significant shows, including both bleeding oil and gas flows, have been reported, supporting our assessment that the basin contains an active petroleum system. The best potential for oil is in the latest Permian to Early Triassic section in the north of the basin. Five major structurally related plays offshore were identified by Maung and others (1997).

The possible offshore extension of the Early Triassic **Lorne Basin** is very poorly known, with no information on its areal extent or thickness. The stratigraphy is likely to be similar to the onshore basin, where a thin section of terrestrial sediments contains no potential source rocks. The presence of numerous large intrusive bodies further downgrades the prospectivity of the basin, and any offshore extension of the Lorne Basin is considered very unlikely to be prospective for petroleum.

A series of stacked and contiguous Mesozoic basins underlie southeast Queensland and northeast New South Wales, and have relatively minor offshore extensions under the continental shelf. The oldest syn-rift rocks are of Middle Triassic age, are known in outcrop as the Nymboida Coal Measures, but are very poorly known under the main basin depocentres. Goscombe and Coxhead (1995) used the term **Nymboida Basin** to describe this sequence. After a hiatus the Nymboida Basin was overlain by the **Ipswich Basin**, which crops out only in the Ipswich area and as small exposures along the margins of the overlying basins, but is far more widespread in the subsurface. Through most of its extent, the Ipswich Basin is overlain by the late Late Triassic to Late Jurassic **Clarence-Moreton Basin**, except in the northeast, where the Ipswich Basin partly underlies the Late Triassic to Early Jurassic **Nambour Basin**.

The **Nymboida Basin** is overmature for oil and currently generating only dry gas. It is most unlikely to contain suitable reservoirs due to its depth of burial and heat flow history, as diagenesis will have destroyed any primary porosity or permeability.

Oil prospects for the **Ipswich Basin** are poor. The kerogen types present indicate that the rocks are more gas-prone than oil-prone. Any Ipswich Basin oil generation would also predate the main period of trap formation in the overlying Clarence-Moreton Basin, but it may source gas for that basin. The Ipswich Basin also has potential as a source of coal-seam methane.

Prospects for the discovery of hydrocarbons in the **Nambour Basin** are poor. The reservoir potential of the Landsborough Sandstone is good, but it crops out extensively and lacks a suitable seal. While the basin sequence is within the oil window, source material is very limited. The Ipswich Basin underlies part of the southern Nambour Basin and could be a source of gas, but the only possible traps would be offshore, where Cainozoic marine sediments have the potential to act as a regional seal.

O'Brien and others (1994) evaluated the petroleum prospectivity of the onshore **Clarence-Moreton Basin**, and divided it into six areas on the basis of level and type of prospectivity. The offshore Yamba Trough falls into Area 5 of O'Brien and others (1994), and is likely to have gas potential. The prospectivity of the more extensive offshore sequence identified by Alder (2001) is unknown, because the age, geohistory and nature of the sediments therein are all unknown. For that reason, its potential prospectivity for petroleum can not be discounted, and it is rated 'possibly' prospective for both oil and gas.

The **Maryborough Basin** is a deep north-northwest trending synclinal structure, and contains a thick sequence of up to 10 km of sediments (and some volcanics) of latest Triassic to Early Cretaceous age (Ellis, 1966). The basin developed between the earliest Triassic and mid-Jurassic as an epicontinental downwarp, probably a foreland depression. Neocomian volcanism and rifting led to a second phase of deposition, before basin inversion in the mid-Cretaceous produced major folding and faulting (Hill, 1994). Subsequent uplift and erosion led to the loss of several km of section from much of the Maryborough Basin, particularly onshore.

The Maryborough Basin is considered to have good potential for gas, sourced from and sealed within the Cretaceous Maryborough Formation. Charge and post-inversion seal are low risk, but reservoir quality is problematical, so explorers would need to seek reservoir sweet spots. Oil is also possible within the Cretaceous section, but less likely due to the timing of trap formation versus oil generation. Reservoirs within the Late Triassic Myrtle Creek Sandstone are likely to be very deep and tight in the central basin, whilst trap breach of any such reservoirs near the basin margin is probable. A key event in basin history is Santonian inversion, which probably breached many older traps, whilst creating new ones in the form of northwest-trending anticlines and fault-bound rollovers. The offshore Cainozoic section is largely unknown. It could conceivably contain sealed hydrocarbon reservoirs, sourced from the Cretaceous section.

Environmental concerns are likely to severely limit petroleum exploration within the offshore Maryborough Basin. The likelihood of gas rather than oil, and tight reservoirs, will add further economic disincentives to offshore petroleum exploration. Onshore however, the Maryborough Basin has had one significant gas show from only five exploration wells drilled, and may prove with further exploration to be a viable gas province.

In addition to these basins, small graben and half-graben associated with Tasman Sea rifting may occur within basement dominated shelf and slope areas. One such feature is known to exist on the continental slope near Bateman's Bay (Colwell and others, 1993), and similar graben are known from the northern end of the Tasman Sea rift (Stephenson and Hill, 2002); these features may be more widespread along the central eastern margin than is currently known. The prospectivity of such graben is currently unknown.

# Introduction and Regional Setting

This report gives a preliminary assessment of the petroleum potential of Australia's east coast, from the southern boundary of the Great Barrier Reef Marine Park (GBRMP) in the north, to the border between New South Wales and Victoria in the south (Figure 1). As petroleum exploration is prohibited within the GBRMP, assessments of coastal areas of central and northern Queensland are not included in the report. Onshore elevation and offshore bathymetry of the study area are shown in Figure 2.

Economic basement in the study area is comprised mainly of Palaeozoic sedimentary, metamorphic and igneous rocks of the Lachlan Fold Belt in southern New South Wales, and the New England Fold Belt further north. Oceanic basalts of the Tasman Basin separate the Australian continent from the Lord Howe Rise, a major continental fragment. In plate tectonic terms, the eastern margin of Australia was a collision zone in the Permian to Early Triassic, went through phases of intracratonic transtensional and sag basin development in the Late Triassic to Early Cretaceous, followed by Late Cretaceous rifting and opening of the Tasman Sea. It is currently a passive margin that has accumulated varying amounts of clastic and carbonate shelf and slope sediments through the Cainozoic. Gravity and magnetics maps of the region are shown in Figures 3 and 4, respectively.

Basement rocks covered by a veneer of Cainozoic sediments underlie a large part of the offshore east coastal region (Figure 1). Of the sedimentary basins known to occur offshore, only the Sydney Basin is relatively well known, and then only from geophysical data as no well has been drilled offshore (Alder and others, 1998). The Maryborough Basin is the next well known offshore, from BMR *Rig Seismic* Survey 91 (Hill, 1994), although the survey did not cover the northern part of the basin. Further south, the offshore Nambour Basin is virtually unknown, as is any possible extension of the underlying Ipswich Basin. Off the NSW north coast, the Yamba Trough of the Clarence-Moreton Basin is known from geophysical data only (Wells and O'Brien, 1994). However, limited data suggest a more extensive sedimentary section in this area (Alder, 2001). Whether this is Clarence-Moreton Basin, underlying Ipswich Basin or a totally new basin is not yet known. Further south, it is not yet known whether or not the small onshore Lorne Basin extends offshore.

In addition to these basins, small graben and half-graben associated with Tasman Sea rifting may occur within basement dominated shelf and slope areas. One such feature containing up to 2.5 km of sediment is known to exist on the continental slope near Bateman's Bay (Colwell and others, 1993). Similar graben are known from the northern end of the Tasman Sea rift (Stephenson and Hill, 2002), and they may be more widespread along the eastern margin than is currently known.

Much of the information used for this report has by necessity been drawn from onshore sources. Only time and new offshore data will tell how valid these extrapolations turn out to be.

## *Sydney Basin*

### Overview

Deposition in the Sydney Basin was largely driven by foreland thrust loading initially directed from the east and later from the north to north-east (Maung and others, 1997). Marine sequences dominated in the Early Permian, and fluvial sediments and coal measures thereafter. It is generally agreed that sedimentation continued through the Jurassic and Early Cretaceous, but rocks of these ages were removed by massive erosion following uplift in the Late Cretaceous, associated with the opening of the Tasman Sea (Alder and others, 1998). During this rifting, extensional normal faulting was superimposed on pre-existing structures.

The Sydney Basin is located along the New South Wales coastline between latitudes 32°S and 36°S (Figure 5), and covers an area of about 59,000 $km^2$, of which 44,000 $km^2$ is onshore (Cadman and others, 1995) and 15,000 $km^2$ offshore (Grybowski, 1992). The Sydney Basin contains at least 6 km of Permo-Triassic marine and non-marine sequences, and is the southernmost part of an eastern Australian super-basin that extends from the hydrocarbon producing Bowen Basin in Queensland through the Gunnedah and onshore Sydney Basins. These basins contain huge reserves of Permian coal, particularly in the Bowen and onshore Sydney Basins, and are Australia's main coal-producing basins. The onshore Sydney Basin contains in excess of 4 km of clastic sediments deposited in major depocentres. Offshore, the Sydney Basin is in water depths of between 0 - 4,500 metres, and includes the thickest section of at least 5 km of sediments (Alder and others, 1998).

Coal seam methane is currently being produced from a pilot plant near Camden in the southern onshore Sydney Basin, but there are no known conventional gas or oil reserves. There have been 8 sub-economic gas discoveries made onshore (Cadman and others, 1995), and numerous wells have recorded gas shows. Eight wells drilled between 1937 and 1982 have recorded oil shows, mainly in the north-eastern part of the onshore basin (Cadman and others, 1995).

Oil shale occurs at several places within the Late Permian coal measures in the west of the Sydney Basin, and was used between 1860 and 1924 to produce kerosene (Mayne and others, 1974), and during World War 2 to produce petrol (Stewart and Alder, 1995). No wells have been drilled offshore, although at the time of writing the current permittees have stated an intention to drill the Biggus Prospect, formerly known as the South Baleen Prospect (Daytona Energy and Bounty Oil & Gas, 2001) offshore Newcastle in 2004/05. The offshore Sydney Basin is thought to be more prospective for gas than for oil (Alder and others, 1998), an assessment that we concur with in this Record. However, we also agree with Arditto (2003) that oil-prone and wet gas-prone Permian source rocks are likely offshore, although timing issues are a major risk factor.

## Current State of Knowledge

More than 115 petroleum exploration wells and several hundred shallower (< 500 m) coal exploration and coal seam methane well have been drilled onshore in the Sydney Basin. The following summary of onshore drilling is largely based upon Maung and others (1997).

The occurrence of coal measures close to Sydney encouraged most of the early geological investigations in the Sydney Basin. The search for coal led in 1885 to the discovery of gas in sandstones of the Triassic Narrabeen Group. The first petroleum exploration well was Richmond-1, located near Richmond, and 3 more wells were drilled in the same area between 1910 and 1921. Shows of natural gas and oil were reported, but there was no commercial production. Belford Dome Ltd tested the Belford Dome for petroleum with the drilling of three wells in 1927. Also in 1927, Oil and Gas Investigations Ltd drilled Loder Dome-1, a well that reached 729 m. Slight gas shows were reported in these wells.

The lack of success on these two prominent anticlinal structures caused a lull in drilling activity for about seven years. In 1935, Tylers Bargo-1 well was drilled a few kilometres west of Bargo. Few details of this well remain, but it terminated at a depth of 1083 m and traces of gas were recorded. Four deep wells, Kulnura-1, Mulgoa-1, Farley-1, and Balmain-1 were drilled between 1935 and 1938. Gas shows were reported in the first three wells, whilst Balmain-1 produced 20 MMCF of gas from the Narrabeen Group between 1944 and 1950. Peak production was 18 MMCF of gas in 1944 (Maung and others, 1997). This was the only commercial production of gas from the Sydney Basin until the commencement of coal seam methane production in the mid 1990s. Only three wells, Camden-2, Baulkam Hills-1 and Mount Hunter-1 flowed moderate gas rates from Permian reservoirs, but all flowed at rates below 1 MMCF/day and were non-commercial discoveries (Maung and others, 1997).

Drilling resumed in the Sydney Basin during 1954, with greater use of available geological and geophysical data. Since then, numerous petroleum exploration wells have been drilled. Some of the wells only penetrated the Permian sedimentary sequence, whereas others penetrated both the Triassic and Permian sequences. Several wells reached effective basement. Although most of the wells were drilled on surface geological structures, some wells were located to test structures based on seismic interpretation and mapping. These wells have provided abundant stratigraphic information and a considerable amount of information about reservoir conditions within the basin. However, none yielded commercial quantities of oil or gas (Maung and others, 1997). A detailed list of all wells drilled in the Sydney Basin up until 1970 is contained in Mayne and others (1974).

Near the western margin of the Sydney Basin, oil shale occurs as high grade torbanite yielding approximately 300 litres of shale oil per tonne as lower grade cannel coal (Stewart and Alder, 1995). These torbanite deposits in the upper part of the Late Permian coal measures were exploited between 1865 and 1924 to produce kerosene for lighting purposes, with the largest deposits at Joadja in the south, and Newnes and Glen Davis in the central west (Mayne and others, 1974). Deposits have also been recorded within the Greta Coal Measures in the north of the basin. From 1939 to 1952 the torbanite deposit at Glen Davis was exploited to produce petrol (Mayne and others, 1974), with one tonne of oil shale yielding an average of 20 litres of crude oil, which in turn gave about 10 litres of refined petrol (Stewart and Alder, 1995).

The offshore Sydney Basin has been explored intermittently since 1964, but only geophysical surveys have been undertaken, and no offshore wells have been drilled at the time of publication. Offshore geophysical surveys over the Sydney Basin are documented in Table 1, which is modified after Maung and others (1977). All seismic data shot in the basin are 2D.

| SURVEY | OPERATOR | YEAR | TYPE | TOTAL KM |
|---|---|---|---|---|
| Terrigal, NSW | Central Coast Oil Ltd | 1964 | Magnetic | 1704 |
| Offshore Sydney Basin | Shell Co of Aust Ltd | 1964 | Seismic | 1497 |
| Sydney-Newcastle (Offshore) | Shell Dev (Aust) P/L | 1966 | Magnetic | 1590 |
| Offshore Sydney | Shell Dev (Aust) P/L | 1967 | Seismic | 113 |
| Broken Bay | Longreach Oil Ltd | 1969 | Seismic | 1400 |
| NSW Marine | Murphy Oil | 1969 | Seismic | ? |
| Teledyne Scientific | Teledyne | 1970 | Seismic | ? |
| South Sydney Basin | Magellan Petroleum | 1970 | Seismic | 64 |
| South Broken Bay | Longreach Oil Ltd | 1970 | Seismic | 92 |
| *Continental Margins Survey 12* | *BMR Marine** | *1971* | *Seismic, bathymetry, gravity,* | *23924* |
| Sealion | Longreach Oil Ltd | 1971 | Seismic | 407 |
| *Continental Margins Survey 15* | *BMR Marine** | *1972* | *Seismic, bathymetry, gravity,* | *?* |
| Offshore Sydney Basin | ESP Exploration (Sydney Oil) | 1981 | Seismic, gravity, | 1742 |
| *BMR Survey 68* | *BMR Marine** | *1987* | *Seismic, bathymetry, gravity,* | *?* |
| Sydney 1:250 000 map sheet | NSW DME | 1989 | Magnetic | ? |
| 1990 Sydney Basin | Santos Ltd | 1990 | Magnetic | 5917 |
| 1991 Seaspray | Santos Ltd | 1991 | Seismic | 603 |
| PEP 11 Biggus | Bounty Oil & Gas | 2004 | Seismic | 1500 |
| ** Only a small part of these BMR surveys are over the Sydney Basin.* | | | | |

*Table 1. Geophysical surveys in the offshore Sydney Basin.*

Central Coast Oil and Shell acquired data in the offshore Sydney Basin in the mid-1960s, and Longreach Oil and Magellan Petroleum acquired 1934 line-km of seismic data in the basin between 1969 and 1971. After a break in exploration, ESP Exploration was awarded permit PEP 9, and acquired 1742 line-km of seismic, gravity and magnetic data in 1981, but relinquished their permit without drilling a well. The NSW Department of Minerals and Energy flew an aeromagnetic survey over the Sydney 1:250 000 map sheet area in 1989, including over part of the offshore basin.

In 1989 Santos were awarded permit PEP 10 over the northern two-thirds of the offshore Sydney Basin. In 1990 they acquired 5917 line-km of aeromagnetic data, mainly in areas not covered by earlier surveys (Grybowski, 1992). Santos also shot 603 line-km of seismic data within their permit in 1991. Six major structural leads were identified (Daytona Energy and Bounty Oil & Gas, 2001), but again the permit was relinquished without a well being drilled. The northern half of the offshore Sydney Basin currently lies within Permit PEP 11, which is held by a joint venture of Bounty Oil & Gas and Electro Silica Oil & Gas. The joint venture has recently acquired new seismic data, and has plans to drill a well at the time of writing. Industry seismic coverage in the offshore Sydney Basin is shown in Figure 6.

**Stratigraphy, Sequences and Tectonics**

Sydney Basin stratigraphy is complex, with significant intra-basin facies variations at most times, as shown in Figure 7, from Maung and others (1997). This is in turn partly due to a complex tectonic history, compounded by palaeogeographic complexity. Stratigraphic relationships for the Permian section are depicted in Figure 8, a SW-NE schematic cross-section of the basin, also from Maung and others (1997). A more detailed account of Sydney Basin stratigraphy than appears below is included in this report as Appendix 1.

The Sydney Basin forms part of a major longitudinal super-basin system, stretching over 1500 km from the Bowen Basin in Queensland, southwards through the Gunnedah and Sydney Basins. The Bowen-Sydney super-basin runs along the entire length of the New England Fold Belt with respect to which it is considered a mid Permian and Triassic foredeep. However, its Early Permian history remains unclear, for example, Schneiber (1993) in a comprehensive review, listed 11 different tectonic models proposed by recent workers. The commonly accepted view is that the Sydney Basin commenced as a tensional volcanic rift between the Lachlan and the New England Fold Belts (Schneiber, 1993; Veevers and Powell 1994, Maung and others, 1997).

According to Veevers and Powell (1994) rifting and associated volcanism began in the Late Carboniferous above the former fore-arc of an Andean-type magmatic arc which had originally developed in response to westerly dipping subduction beneath the Lachlan Fold Belt. This subduction was associated with the convergence of what is now the New England Fold Belt. The cessation of subduction along this margin, and its migration to a more easterly position, led to subsequent Permian deposition being governed by the conversion of the basin into a foredeep depression, adjacent to the mainly west to southwest overthrusted New England orogenic terranes.

It was during this foredeep loading episode that the regionally extensive potential petroleum source-rock (coal bearing) facies of the Late Permian Tomago, Newcastle and Illawarra Coal Measures were deposited in marginal to non-marine environments (Figure 7). Whereas the Early Permian was dominated by marine deposition, the Middle to Late Permian was subjected to regressive clastic fill derived from the arc-related, acid-intermediate to basic-intermediate, volcaniclastic sands shed from the New England Fold Belt then experiencing episodic uplift. By contrast, intervening periods of structural quiescence and periods of foreland bulging were marked by deposits of quartz-rich sands shed from the western Lachlan Fold. Extensive uplift at the end of the Permian culminated in the Triassic being dominated by fluvial deposition and marine retreat from the onshore areas (Maung and others, 1997).

During the Permian the Bowen-Sydney basin complex formed part of eastern Gondwana which at that time lay adjacent to the South Pole. Evidence of glaciation is widespread throughout Early Permian (Packham, 1969). Most glaciation finished around the top of the Sakmarian (P.E. O'Brien, personal communication). Conditions became warmer in the latest Permian (Archbold and Dickins 1991).

The youngest preserved sediments in the Sydney Basin are the Middle Triassic Wiannamatta Group (Figure 7). However maturity trends and burial history analyses imply that a substantial amount (2-3 km) of Jurassic to Cretaceous aged sediments accumulated after a hiatus in the Late Triassic (Mayne and others, 1974; Sullivan and others, 1995; Maung and others, 1997). There is evidence of Early Jurassic (Sinemurian) spores in diatreme sediments from the Sydney Basin (Bradshaw and Yeung, 1992). Although this period of the basin's history is largely unconstrained it is now generally agreed that following on-going Jurassic-Cretaceous sedimentation the Sydney Basin experienced stable conditions, probably with minor erosion, from the Early Cretaceous to the mid Cretaceous. After this time the Basin experienced rapid uplift and erosion, in response to the commencement of seafloor spreading in the Tasman Sea. This denudation, together with the subsequent passive margin thermal sag phase, resulted in cooling of much of the Sydney Basin during the Late Cretaceous to Palaeogene, and the creation of the current structural boundaries.

Major events affecting the Sydney Basin and palaeogeography are summarised in Figure 9.

Although the onshore Sydney Basin limits are well defined, either by structural boundaries, (eg. the Hunter-Mooki Thrust), or depositional onlap edges onto the Lachlan Fold Belt to the south and west, the original easterly (offshore) extent of the Basin remains conjectural. Currently the eastern edge of the Basin is truncated by the continental slope. During the Late Cretaceous the easternmost portions of the Sydney Basin were dismembered following rifting and the commencement of seafloor spreading in the adjacent Tasman Sea Basin.

Seismic data show no evidence of thick Jurassic or Cretaceous synrift deposits preserved across the continental shelf. However, bottom samples from across the shelf and slope, adjacent to the onshore Sydney Basin (AGSO, 1993) have recovered late Mesozoic aged sediments. In many cases the retrieved samples are indurated and contain abundant volcanics suggesting an active volcanic synrift phase. Nevertheless, the absence of any thick Mesozoic sequences within the Sydney Basin is attributed to Cretaceous uplift and erosion having removed younger sequences. Preservation of Mesozoic synrift sediments is most likely confined to locations east of the present shelf break, either across the down-faulted continental slope or on dismembered and dispersed margins of the Tasman Sea, across the Dampier Ridge and Lord Howe Rise. Across the shelf the rift-onset and break-up unconformities coincide. Up to 700 m of post-breakup, Oligocene to Recent carbonate and terrestrially derived clastics, unconformably overlie sub-cropping Permian or Triassic aged sediments (Maung and others, 1997).

## Potential Source Rocks

Significant dispersed organic matter in the Wollombi and Early Permian Greta Coal Measures is comprised of exinite, indicating potential for oil sources (Cadman and others, 1998).

The Late Permian coal measures attain a thickness of about 1600m at the coast between Newcastle and Terrigal-1, but thicken and dip offshore (Brakel, 1989; Figure 10). In the northern Sydney Basin they comprise the Tomago Coal Measures and the Newcastle Coal Measures. The upper Tomago Coal Measures have about 6% coal whereas the Newcastle Coal Measures are about 12% coal. The high inertinite and vitrinite content of Sydney Basin coals indicate that they are primarily a potential source of gas. The occurrence of numerous oil seeps indicates that these same facies have some oil source potential, as suggested by the relatively high proportions of liptinite. This is supported by a comparison of maceral content that shows that the Upper Permian Sydney Basin coal measures have higher inertinite content than the oil-prone Toolache Formation of the Cooper Basin (Maung and others, 1997). These Late Permian coal measures also contain oil shales in the west of the basin (Stewart and Alder, 1995), and if similar facies are present in the east they could enhance the prospectivity of the offshore basin.

Smyth (1983) considered the thick marine siltstone sequences of the Branxton and Mulbring sequences to be regional source rock sequences, containing significant terrestrially derived TOC in the onshore Sydney Basin and probably the adjacent Offshore Syncline. Further east across the Offshore Uplift (Figure 5), the oil-prone nature may increase as marine components increase. Clayey siltstones have been identified as sourcing oil in several onshore Sydney Basin wells (Maung and others, 1997). Substantial quantities of methane have been generated within the Sydney Basin coal measure sequences to the point that significant exploitation of coal bed methane has commenced.

Maung and others (1997) interpret the offshore Tomago Coal Measures to be truncated both across the Offshore Uplift and the shallowing flanks of the offshore New England Fold Belt. On some seismic lines, an interval of relatively high amplitude, laterally discontinuous, high frequency reflectors suggests a significant proportion of coaly facies, which may coincide in part with offshore equivalents of the Greta Coal Measures. Alternatively it may represent distal deltaic facies, time equivalents of the Greta Coal Measures and Snapper Point Formation, facies which are not otherwise represented in the onshore (Maung and others, 1997).

## Potential Reservoirs, Seals and Trap Types

**The principal potential *reservoirs* identified by Maung and others (1997) and Alder and others (1998) include:**

- Lower Permian, high-energy near shore, wave dominated deposits of the Wasp Head Formation and parts of the Snapper Point Formation and equivalents. The former occurs mainly in the centre of the basin, whilst the Snapper Point Formation is more widespread. Both units have no reservoir facies equivalents in the north of the basin (Figure 7). The Snapper Point Formation has porosities of up to 16%, but primary porosity has been significantly reduced by diagenesis, and permeability is very low, ranging from 1.5 to 98.5 md (Ozimic, 1980).

- Outer-shelf systems of the Lower to Upper Permian Wandrawandian Formation and Middle Branxton Formation. Whilst these formations are very silty and lack porosity onshore, it is possible that better reservoir facies could occur offshore.
- Upper Permian wave dominated delta systems of the Nowra and Muree Sandstones, especially the reworked regressive, quartz rich units. These occur across the basin (Figure 7), and have porosities of between 5% and 12%, but very low permeability of from 1.0 to 23.4 md (Ozimic, 1980).
- Sandstones associated with minor marine incursions during the Late Permian, distal marine equivalents of the coal bearing deltaic systems.
- Triassic Narrabeen Group now confined to the Offshore Syncline. Onshore, this Group was subjected to extensive early burial diagenesis (Bai and others, 2001). Nonetheless, Arditto (2003) regarded the Narrabeen Group as the best potential reservoir target in the offshore southern Sydney Basin. Narrabeen Group sandstones have recorded porosities of between 3% and 31% (Maung and others, 1997). The diagenesis of the Narrabeen Group was described in detail by Bai and others (1991).

**Potential *seals* identified by Maung and others (1997) include:**

- Thick sequences of marine siltstones, equivalents of the Mulbring and Berry Siltstones, and the Branxton Formation and Wandrawandian Siltstone would act as regional seals to contained sandstone units, such as the Nowra and Muree Sandstones.
- Siltstones, claystones and mudstones of the Early and Late Permian coal measure sequences would act as local seals to interbedded fluvio-deltaic sand units, offshore equivalents to the Watts Sandstone and Marrangaroo Conglomerate (Robertson Research, 1981).
- Interbedded red and green claystones provide effective seals to individual fluvial and sand bodies of the Narrabeen Group.
- The Bald Hill Claystone provides and effective seal near the top of the Narrabeen Group.
- The shaly facies of the Wianamatta Group provides a regional seal for the Hawkesbury Sandstone.
- Intraformational seals should be well developed in the offshore Kulnura Marine Tongue.

***Trap types* are expected to be mainly structural. Five principal structural trapping mechanisms were recognised by Maung and others (1997):**

1. Transpressional, wrench-related structures within the Offshore Syncline and Newcastle Syncline. These are north-northeast oriented and probably en echelon, being intersected by east-northeast trending cross faults, presumably related to extensional tectonics associated with the Tasman margin rifting.
2. Overthrust traps located along the western margin of the Offshore Uplift. These are anticipated to include some four-way dip closures, and in the north at least a truncated Lower Permian sequence would be involved.
3. Mild basin inversion structures, due to southerly directed thrusting along the southern flank of the Offshore Uplift bordering the Newcastle Syncline.

4. Extensional, down to the basin margin normal fault bound blocks on the eastern flank of the Offshore Uplift.
5. Sub-thrust plays, along the eastern edge of the Offshore Syncline where former foreland deposits have been overthrust during subsequent westerly movements of the Offshore Uplift.

The above analysis by Maung and others (1997) doesn't include the potential for stratigraphic and combined structural-stratigraphic traps. Although speculative, the presence of such potential traps can not be excluded from the range of possibilities. More detail on Sydney Basin stratigraphy and structural styles is given in Appendix 1, including seismic sections across several potential prospects and leads, such as the Biggus Prospect (Figure 36), formerly known as the South Baleen Prospect (Daytona Energy and Bounty Oil & Gas, 2001).

**Maturity and Timing**

Burial history analyses, which attempt to model the anticipated maturation trends within the Sydney Basin, have typically involved various combinations of additional post-Triassic burial and elevated heatflow pulses. Figure 11 shows an example of one such burial history plot, based on the East Maitland well (Grybowski, 1992). It was modelled assuming present day heat flow with spikes of $70mW/m^2$ during periods corresponding to the Hunter - Bowen Orogeny and Tasman Sea rifting. The plot also incorporates on-going deposition during the Jurassic and Cretaceous, followed by 3300 m of erosion. Maung and others (1997) considered that 1000 - 2000 metres of Jurassic - Cretaceous burial followed by uplift was more likely, and thus the burial history plot shown in Figure 11 overestimated the levels of maturity and hence the times for the onset of oil and gas generation and expulsion. Nevertheless, Maung and others (1997) considered that the assumption that the maximum depth of burial was attained at about 100 Ma was reasonable, and similar to burial history trends elsewhere in eastern Australia (Korsch and Totterdell, 1996).

Bai and others (1993) also provided detailed burial history modelling of the Sydney Basin. Again their modelling had subsidence continuing from the Permian to mid-Jurassic times, with ensuing stable conditions from the Middle Jurassic to Late Cretaceous, followed by rapid uplift and erosion to 10 Ma. Stable conditions dominated from 10 Ma until the present day. This is also similar to the burial history adopted by Middleton and Schmidt (1982) which puts the time of maximum burial somewhat earlier than shown in Figure 11, at 165 Ma, within the Middle Jurassic.

In each case some hydrocarbons were probably generated from Early Permian sources during the Triassic. Late Permian source rocks commenced generating between the Middle Jurassic and Mid to Late Cretaceous, depending upon the degree of additional burial favoured. Elevated heatflow during Tasman Sea rifting presumably caused an additional generative pulse at that stage. Oil generation and migration from the Upper Permian Illawarra Coal Measures occurred in the Early Cretaceous (Eadington and others, 1991). Extract analysis of the Picton and Coal Operations Australia Limited bore hole samples indicates that oil is still being generated, probably from Late Permian silty and coaly facies in the onshore southern and central portions of the Sydney Basin (Maung and others, 1997).

There is only limited information on migration within the Sydney Basin. The migration of hydrocarbons through reservoir rocks is recorded by the entrapment of oil and gas within fluid inclusions. Fluid inclusion analysis from a small number of samples within the Narrabeen Group and Illawarra Coal Measures has been undertaken. Bai and others (1993) describe the results of a study from three stratigraphic intervals; in the lower part of the Upper Bulgo to the upper part of the Scarborough Formation, from the Winton Formation, and from the Lower Shoalhaven Group. They interpreted the timing of oil migration by integrating data on the temperature of cementation reactions, burial history, and the location of liquid hydrocarbon fluid inclusions relative to the textures and superposition of diagenetic minerals. Sandstones in the Narrabeen Group contain oil inclusions in quartz overgrowths and healed fractures indicating that at least some oil migration took place. However the sandstones are water-wet and only low saturation can be inferred. Because the oil inclusions exhibit white and blue fluorescence they are interpreted to be of high maturity. The presence of quartz overgrowths suggests that oil migration took place during quartz overgrowth cementation and probably also after crystallisation of overgrowths. Eadington and others (1991) reported that migration in the Scarborough Sandstone took place in Jurassic times.

The fluorescing liquid hydrocarbon inclusions in quartz overgrowths demonstrate that oil in small quantities migrated through sandstones of the Scarborough and Lower Bulgo units during and probably also after quartz cementation, with at least two phases of oil migration occurring within the Winton Formation. Less mature oil in small quantities migrated through these sandstones prior to and during quartz cementation. Mature oil in large quantities migrated and accumulated in these sandstones during, and probably also after, crystallisation of quartz overgrowths (Bai and others, 1993).

Gyrbowski (1992) makes reference to fluid inclusion work on samples recovered from Campbelltown-2 well, located in the southern onshore Sydney Basin. This showed maximum heat flow in the Early Cretaceous resulting in oil generation and migration from the Upper Permian Illawarra Coal Measures (Eadington and others, 1991). Conversely, the geochemistry of oil extracts suggest that the oils at the Picton wells, located near to Campbelltown-2, are mature and sourced from terrestrially derived organic matter in the fine grained lithologies rather than from the coals themselves. Maturity trends would suggest that the oil has not migrated far, and similar conclusions have been reached in oil extracts from fractured lithic sands encountered whilst drilling for coal in the Wyong area of central Sydney Basin (Maung and others, 1997).

Vitrinite reflectance values for wells within the onshore Sydney Basin show that in the onshore the pre-Triassic section is mature to over-mature for oil generation (Maung and others, 1997). At East Maitland-1 the floor of the oil window (VR at 1.3%) lies at approximately 1500 m. Based on Shiboaka and others (1973), and assuming that the interpreted vitrinite reflectance gradients in the adjacent onshore area are indicative, offshore equivalents of the Lower Permian Greta Coal Measures lie within the gas to gas-condensate window. In the northern Sydney Basin, thermal maturation of the coal measures had reached a stage of early mature for oil generation prior to exhumation which resulted in their surface exposure. Higher surface vitrinite reflectance values in the south have been postulated to reflect a higher palaeo-heat flow in the Sydney-Wollongong area that caused the coal measures to pass into the gas window. However, this may in part be an attribute of vitrinite reflectance suppression due to marine influence during the deposition of some northern Sydney Basin coals. George and others (1994), for example, suggest that vitrinite may have been suppressed in the Greta Coal Measures by up to 0.25% Ro. Herbert (1987) demonstrated that the gas in the deepest part of the onshore basin is ethane-rich compared to gas near the basin perimeter, and that the carbon-dioxide content of the gas also increases towards the onshore basin deep, centred on the Cumberland Plain. This distribution is attributed to increasing maturity towards the depocentre. Herbert (1987) noted the coincidence of areas of ethane and carbon-dioxide rich gas with the 1.2% isoreflectance contour at the top of the Late Permian Coal Measures. This would imply that most of the southern offshore Sydney Basin is beyond this level of maturity, and hence overmature for oil generation (Maung and others, 1997).

A thermal event preceding uplift is thought to have occurred somewhere between 118 and 83 Ma (Maung and others, 1997). Abnormally high vitrinite reflectance values and trends in the onshore Sydney Basin, which are largely transparent to Permian structuring, suggest at least 1-2 km of additional sediment cover, but there are no remnants of that cover remaining on the onshore surface geology. Sample dredging in the offshore suggests continuity of Triassic - Jurassic sedimentation, with late Mesozoic sediments comprising a significant fraction of sediments across the lower slope. Fluid inclusion, authigenic illite ages and isotope work indicate that a period of high heat-flow between 146 and 83 Ma accompanied this uplift and erosion (Maung and others, 1997).

The relative timing of trap formation is speculative, given the absence of any direct offshore well control. Based on the five trapping mechanisms outlined in Maung, 1997 (see above), trap types (2) and (4) formed in the earliest Permian, type (1) traps formed in the earliest Permian-Triassic, type (3) traps formed in the early Late Permian-Late Permian, and type (5) traps formed during the Late Carboniferous. Other than the above trapping mechanisms, there are also Cretaceous extensional trapping mechanisms associated with rifting prior to the opening of the Tasman Sea.

Figure 12 is a petroleum systems summary for the Sydney Basin. Whilst the basin is prospective for gas at many stratigraphic levels, the best potential for oil is in the latest Permian to Early Triassic section in the north of the basin.

**Key Unknowns**

Late Carboniferous volcanic rocks interpreted by Maung and others (1997) could alternatively be of mid-Permian age. If so, Late Permian Coal Measures could occur along the eastern flanks of the Offshore Uplift, providing better access to source rocks for reservoir sequences within the overlying Triassic section.

Diagenesis appears to have adversely affected most of the Sydney Basin on a regional scale. This diagenesis reflects the present geometry of the basin and the additional 2-3 km of Mesozoic sediments that was deposited and subsequently eroded. Diagenesis may not have been as severe across palaeo-highs where additional burial was restricted, such as the onshore Lochinvar Anticline and the Offshore Uplift.

Late Permian sediments were generally deposited in low energy marine environments, resulting in poor sorting with a higher proportion of fines that clogged up the pore throats. Early Permian sediments are better sorted, indicating that reservoir quality should increase toward the east, where the rocks are likely to have been deposited in high-energy, shoreline and shallow marine reworking palaeoenvironments.

Smyth (1983) confirmed that the thick marine siltstone of the Branxton and Mulbring sequence could constitute a potential source rock. Further east across the Offshore Uplift, the oil prone nature may increase if probable deeper water lithologies have a higher organic content, particularly within the developing Newcastle Syncline and on the outboard flank of the Offshore Uplift.

Oils present in the onshore Sydney basin are from terrestrial dominated environments. Biomarkers suggest a clay-rich depositional environment rather than a coal swamp, suggesting the source was associated with coal facies, but not derived from the coals themselves (Maung and others, 1997). Toward the east the Permian coal section could have had more marine influence, improving its ability to source oil.

The petroleum prospectivity of the offshore Sydney Basin is dependent upon it having had a different palaeogeographic setting to the onshore Sydney Basin. Reservoir quality and source potential of the offshore Sydney Basin are considered prospective, provided that deeper marine palaeoenvironments were present. These conditions could have provided a higher-energy environment for increased reservoir quality, and an increased source potential.

**Environmental Sensitivities**

The offshore Sydney Basin underlies whale migration paths between May and October. The coastal area is also extensively settled, including residential and tourist areas, so some sensitivity particularly to near-shore exploration activities could be expected. Major shipping routes also pass through the area, and international communications cables have been laid on and beneath the seabed.

**Conclusions**

The offshore Sydney Basin contains at least 6,000 m of Permian to Triassic marine and non-marine sequences unconformably overlying middle to lower Palaeozoic igneous, volcanic and metasedimentary rocks constituting economic basement. Whereas the onset of Sydney Basin deposition was perhaps triggered by rifting, deposition was largely driven by foreland thrust loading initially directed from the east and later from the north and northeast. Marine sequences, incorporating volcaniclastic lithologies, dominated in the Early Permian. Mainly fluvial deposition commenced in the late Early Permian and dominated thereafter. Towards the top of these cycles thick coal measure facies were deposited, particularly in the Late Permian.

The post-Triassic history of the basin is largely unconstrained because subsequent uplift and erosion removed younger sediments, but it is generally agreed that it experienced on-going deposition and subsidence during the Jurassic, prior to a stabilisation and possibly minor erosion, throughout the Early Cretaceous.

Subsequently, the Sydney Basin experienced rapid uplift and extensive erosion as a precursor to, or in response to the commencement of seafloor spreading in the Tasman Sea. Following rifting and dismemberment of the eastern Australian margin in the Late Cretaceous, the offshore Sydney Basin now lies on the margin of the deep, oceanic Tasman Sea Basin. During rifting, down-to-the-east normal faulting was superimposed onto pre-existing structures.

Whilst the Sydney Basin is considered gas-prone numerous significant shows, including both bleeding oil and gas flows, have been reported, supporting the assessment that the Basin contains an active petroleum system. The best potential for oil is in the latest Permian to Early Triassic section in the north of the basin (Figure 12).

Structural growth of the Offshore Uplift from the earliest Permian has important implications for petroleum exploration, as it provided a major source of clastics (Maung and others, 1997). In addition its thrust load onto the eastern margin of the Lachlan Fold Belt provided a major mechanism for development of the proto-Sydney Basin, and controlled palaeogeography and depositional patterns. Maung and others (1997) identified regions of possibly anoxic or restricted seawater circulation favourable to the preservation of organic material, and also concluded that areas around the emerging high were subjected to marginal and shallow marine deposition favourable to enhanced reservoir development.

Five major structurally related plays were identified by Maung and others' (1997) seismic interpretation of the offshore Sydney Basin.

1. Crestal anticlines along the upthrust western margin of the Offshore Uplift involving Early Permian reservoirs sealed intraformationally, and regionally by shallow fine grained marine sequences of the overlying Cainozoic sequences. These may be sourced by either up-dip migration from the east or vertically up extensional faults from kitchen areas to the immediate west in the Offshore Syncline.

2. Fault related anticlines involving both compressional and extensional faulting across the eastern flank of the Offshore Uplift, with reservoir objectives within the reworked transgressive sand units of the Early Permian. These would include equivalents of the Wasphead and Snapper Point Formations, sealed regionally by Wandrawandian Siltstone equivalents and sourced either from the regional seal or from interbedded marine siltstones or coaly facies, equivalent to the Clyde River Coal Measures.

3. Sub-thrust plays involving Early Permian primary and fracture related reservoir targets where critical closure is provided by overthrusting of the Offshore Uplift during the late Early or early Late Permian. Sourcing would be from anticipated thick marine and terrestrial detritus deposited within possibly anoxic deeper waters in the Offshore Syncline area.

4. Transpressional wrench related structures within the Offshore Syncline, probably compartmentalised by northeast trending normal faults which would provide vertical migration access into shallower reservoirs. Principal reservoir objectives

would be the cleaner, better-sorted outer shelf equivalents of the onshore Wandrawandian Siltstone and middle Branxton Formation, and the wave dominated delta systems of the Nowra and Muree Sandstones where preserved.

5. Mild basin inversion structures associated with underthrusting and emergence of southerly directed thrust fronts onto the shallowing flank of the Newcastle Syncline. Sourcing would be from offshore, deltaic equivalents of the Greta Coal Measures and marine siltstones of the Branxton Formation. Potential reservoirs may exist up to the level of the Muree Sandstone, and again principal targets would be sought in high-energy, reworked deposits.

Maung and others (1997) also identified a number of play fairways and potential leads in the offshore Sydney Basin, mainly in the area of the Offshore Syncline and western Offshore Uplift (Figure 13). The current holders of Petroleum (Submerged Lands) Act Permit PEP11 have also identified a number of leads in this area (Daytona Oil and Bounty Oil & Gas, 2001). At the time of writing, the Biggus Prospect is scheduled to be drilled in 2004/05; this has the potential to contain up to 1.2 TCF of gas (Bounty Oil & Gas website, January 2004).

# *Lorne Basin*

## Overview

The Lorne Basin is situated on the east coast of New South Wales, and covers some 500 $km^2$ onshore; it may have a possible offshore extension (Figure 1). Although described as a roughly circular basin by Packham (1969), it is in more detail a double structure with a north and south lobe, the overall dimensions being approximately 20 km in an east-west direction and 35 km in a north-south direction (Pratt and Herbert, 1973; Figure 14).

The Lorne Basin is a small, intramontane, Triassic basin formed over the New England Fold Belt. Terrestrial sedimentation into this basin was probably initiated by activity along pre-existing surrounding major faults and serpentine belts. Although situated between two major sedimentary basins that contain Triassic rocks, the Sydney Basin and the Clarence-Moreton Basin, the Lorne Basin has no direct connection with either of them. Pratt and Herbert (1973) have correlated the Lorne Basin sequence with the Early Triassic Narrabeen Group of the Sydney Basin.

The Lorne Basin is not considered to have any significant petroleum potential. The thin sedimentary section of terrestrial lithologies with no potential source rocks and the presence of numerous large intrusive bodies do not encourage petroleum exploration (Bembrick, 1976). The possible offshore extension of the Lorne Basin is unknown, but if an offshore component is present the stratigraphy is likely to be similar to the onshore basin. If present, the offshore basin is also considered very unlikely to be prospective for petroleum.

## Current State of Knowledge

The following history of geological investigations of the Lorne Basin is from Pratt and Herbert (1973). After the first recognition of Triassic rocks in the vicinity of Camden Haven by Carne (1897), the sequence was defined more precisely by Voisey (1939) who described and named the *Camden Haven Series* and the Lorne Triassic Basin. Packham (1969) later formalised the terminology to the *Camden Haven Group* within the Lorne Basin. Subsequently, Pratt (1970) considerably revised the existing stratigraphy after carrying out detailed mapping. Herbert and Burg (1972) made further slight modifications to the general stratigraphic and environmental concept of the sequence during a reconnaissance ceramic survey of the Lorne Basin. Pratt and Herbert (1973) reviewed the Lorne Basin onshore, and further refined the stratigraphy to that which is accepted today.

It is not known whether or not the Lorne Basin extends offshore, but it probably underlies at least part of the continental shelf. An extension under the continental slope is more uncertain, given the timing (Late Cretaceous) of Tasman Sea rifting, but can not be totally discounted due to the absence of seismic data in the area.

## Stratigraphy, Sequences and Tectonics

The area surrounding the Lorne Basin was structurally stabilised by the Late Permian (Scheibner and Glen, 1972). Terrestrial sedimentation into the intramontane Lorne

Basin was initiated during the Early Triassic by block faulting. Elevated blocks of the jasper and quartzite-rich Myra Beds supplied coarse detritus into the developing basin (Pratt and Herbert, 1973).

All the sediments of the Lorne Basin belong to the Camden Haven Group, that rests unconformably on Permian and other Palaeozoic rocks (Packham, 1969). Pratt and Herbert (1973) established the current stratigraphy within the Group (Figure 15).

The Camden Head Claystone is up to 75 m thick near the coast, but thins inland and is absent in the west of the basin. It comprises a sequence of red-brown claystone and siltstone with lesser amounts of grey, plant fossil-bearing siltstone, sandstone and conglomerate, and usually has a thin basal conglomerate (Pratt and Herbert, 1973). The Laurieton Conglomerate is a red, pebble to cobble conglomerate with minor granule conglomerate, sandstone and red-brown claystone beds. It ranges in thickness from 210 m in the west of the basin to 45 m on the coast (Pratt and Herbert, 1973). It both diachronous with and overlies the Camden Head Claystone (Figure 15). The youngest formation of the Camden Haven Group is the 75 m thick Grants Head Formation. The nature of its contact with the Laurieton Conglomerate is unclear due to poor exposure, and it is hard to trace over the western basin for the same reason. The Grants Head Formation grades upward through interbedded sandstone and conglomerate, to cross-bedded sandstone interbedded with laminated sandstone and grey siltstone (Pratt and Herbert, 1973).

Pratt and Herbert (1973) suggested that the Laurieton Conglomerate was deposited from the west as large alluvial fans debouching onto a desert plain or playa now represented by the Camden Head Claystone. They suggested a fluvial origin for the overlying Grants Head Formation, with meandering streams producing channel sandstones and overbank sediments.

Thin coal beds less than 0.3 metres thick have been recorded in rail cuttings and shafts in the Johns River area, and in rail cuttings between Herons Creek and Wauchope (Voisey, 1939). The exact stratigraphic position of the coal is unknown, and the occurrence is regarded as uneconomic (Herbert, 1975). The palaeoenvironments postulated for the three formations of the Camden Haven Group suggest that the coal is probably from the Grants Head Formation.

Post-depositional deformation of the Lorne Basin has been slight. The western part of the basin has been gently folded, with dips recorded around the periphery rarely exceeding 15 degrees to 20 degrees towards the centre. It is possible that these dips may be due in part to initial sedimentary slopes. Vertical dips occurring around the rim of Mount Juhle appear to have been produced by the laccolithic intrusion of a Cainozoic microgranite (Pratt and Herbert, 1973).

**Potential Source Rocks**

There are no source rocks in the onshore Lorne Basin, which is currently overlain by only a thin veneer of Cainozoic fluvial sediments. The basin almost certainly had a thicker cover in the past, given the intrusion of Cainozoic microgranites. The organic content of all formations appears to be very limited, although some thin coals have been recorded in what Pratt and Herbert (1973) described as a ‘red bed’ succession.

## Potential Reservoirs, Seals and Trap Types

Channel sandstones within the Grants Head Formation could potentially form reservoirs. Such reservoirs would require intraformational seals, which are considered unlikely given the silty nature of the overbank deposits within that formation. Possible trap types are limited, given the small amount of post-depositional structuring in the basin.

## Maturity and Timing

In the west of the basin, Lorne Basin rocks are too thin, immature, and covered by insufficient overburden to have generated hydrocarbons, even if a thicker cover may once have been present. They are entirely Early Triassic in age. The eastern part of the basin was intruded by microgranites during the Cainozoic (Pratt and Herbert, 1973), and sediments here will have been variably cooked depending upon proximity to these intrusions. There is likely to be a small area between the thin immature sediments and the thin intruded sediments which was in the petroleum generation window in the Cainozoic, but there is no evidence that hydrocarbons have been generated, probably due to the absence of a source rock.

## Key Unknowns

The possible offshore extension of the Lorne Basin is very poorly known, with no information on its areal extent or thickness. The stratigraphy is likely to be similar to the onshore basin, and the offshore basin is considered very unlikely to be prospective for petroleum.

## Environmental Sensitivities

The offshore Lorne Basin underlies whale migration paths between May and October. The coastal area is also extensively settled, including residential and tourist areas, so some sensitivity to near-shore exploration activities could be expected. Major shipping routes also pass through the area. Onshore there are a number of Nature Reserves.

## Conclusions

The Lorne Basin is not considered to have any significant petroleum potential. The thin sedimentary section of terrestrial lithologies with no potential source rocks and the presence of numerous large intrusive bodies do not encourage petroleum exploration (Bembrick, 1976).

## *Nymboida, Ipswich, Nambour and Clarence-Moreton Basins*

### Overview

A series of stacked and contiguous Mesozoic basins underlie southeast Queensland and northeast New South Wales (Figure 16), and have relatively minor offshore extensions under the continental shelf. The oldest syn-rift rocks are of Middle Triassic age, and are partly equivalent in age to the Esk Trough sequence. They are known in outcrop as the Nymboida Coal Measures but are very poorly known under the main basin depocentres. Goscombe and Coxhead (1995) used the term Nymboida Basin to describe this sequence. After a hiatus the Nymboida Basin was overlain by the Ipswich Basin, which crops out only in the Ipswich area and as small exposures along the margins of the overlying basins, but is far more widespread in the subsurface. Through most of its extent, the Ipswich Basin is overlain by the late Late Triassic to Late Jurassic Clarence-Moreton Basin, except in the northeast, where the Ipswich Basin partly underlies the Late Triassic to Early Jurassic Nambour Basin (Figure 16).

The Ipswich Basin is an important coal mining area in its main outcrop area. There is also evidence from wells in overlying basins that it has produced oil and gas in its deeper section. There have been many hydrocarbon shows in the Clarence-Moreton Basin, including sub-commercial gas discoveries. This basin is thick enough to have sourced its own petroleum, as well as trapping that produced by the Ipswich Basin. The Nambour Basin is currently too thin to have generated its own petroleum, vitrinite reflectance data suggest that it may have originally been much thicker before erosion. Virtually every well drilled into this basin has recorded hydrocarbon shows, but many if not all of these are probably from an Ipswich Basin source.

Offshore, the Ipswich/Nambour stacked Basins certainly underlie Moreton Bay, and probably extend under at least the continental shelf. The Clarence-Moreton Basin has only a small known offshore extension south of Evans Head, the Yamba Trough (Wells and O'Brien, 1994). Alder (2001) identified a much more extensive sedimentary section offshore northern New South Wales, that he assigned to either the Clarence-Moreton Basin or the underlying Ipswich Basin. There is no age control on the sediments, but we suspect that they are most likely to correlate with the Ipswich Basin, based upon the tectonics of the Clarence-Moreton Basin. Alder also proposed that the offshore section might instead be equivalent to the Nambour Basin (Alder, 2001), and this idea may have some merit. However, a contiguous extension of the Nambour Basin that far south is unlikely, given that over 150 km of Beenleigh Block basement straddles the coast around the State border.

### Current State of Knowledge

The onshore Ipswich Basin is very well known in its main area of outcrop, which includes the Ipswich Coalfield. Coal was discovered near Ipswich in 1824 and mining operations commenced in 1846. An extensive drilling program by the Department of Mines to test the Ipswich Coalfield began after the Second World War and was completed in 1969. Since 1960, in excess of one million tonnes of coal has been mined annually (Cranfield and Schwarzbock, 1976a). In New South Wales, small areas of outcropping Red Cliff Coal Measures and Evans Head Coal Measures are assigned to the Ipswich Basin. The offshore extent of the Ipswich Basin is not well known because of very sparse seismic data coverage.

Since the first petroleum exploration well in 1920, 19 exploration wells and five Department of Mines stratigraphic bores have been drilled in the Ipswich Basin. Nearly half of the exploration wells were less than 250 metres deep. Five deep exploratory wells have penetrated the Ipswich Basin sequence between 1934 and 1969: four onshore and one on an offshore island. No significant show of oil or gas was recorded from any of these holes, although there were minor indications of methane (Cranfield and Schwarzbock, 1976a).

The onshore Clarence-Moreton Basin is well known in outcrop, with AGSO Bulletin 241 by Wells and O'Brien (1994) being the current definitive text. The following exploration history is derived from Cadman and others (1998).

The first indication of hydrocarbons in the Clarence-Moreton Basin occurred in 1897, when gas flowed from a coal bore drilled near the town of Grafton. Further gas shows were encountered in the Grafton-1 water bore drilled in 1902 and in a scouting hole, Rosewood-1, drilled in 1907.

In the 1920's and 1930's, a handful of stratigraphic holes were drilled in the basin without encountering significant signs of hydrocarbons. A concerted petroleum exploration effort in the Clarence-Moreton Basin did not commence until the 1950's when a number of exploration wells were drilled to test surface anticlines. Between 1958 and 1969 Clarence River Basin Oil Exploration Company NL drilled six wells on the most significant of these structures, the Clifden Dome. The Clifden-2 well located in the south of the basin, on the western flank of the Clarence Syncline, flowed gas at 2830 $m^3$/day after blowing out at a depth of 592 metres.

Further exploration drilling on mapped surface anticlines was undertaken during the 1960's and early 1970's (seismic coverage in the basin was sparse and of poor quality at this time). Hogarth-2 was drilled in 1970 approximately 80 km north of the Clifden-2 discovery, to test a four-way-dip closure on the western flank of the Clarence-Logan Sub-basin, and flowed gas on test at 14 000$m^3$/day from the Heffer Creek Sandstone Member of the Koukandowie Formation. The only well drilled during this period that was sited using seismic data was Kyogle-1, drilled to test the Kyogle Anticline in the northern Logan Sub-basin. The well encountered oil shows in the Marburg Subgroup and gas shows in the Walloon Coal Measures.

A fresh stimulus to exploration in the Clarence-Moreton Basin was provided in the early 1980's by the release of three petroleum exploration permits covering the basin by the New South Wales government. A number of multi-fold seismic surveys were conducted at this time and all showed a significant improvement in data quality over the earlier analogue data shot in the basin. Several exploration wells were also drilled but all were plugged and abandoned as dry holes. Currently, seismic coverage of the Clarence-Moreton Basin is sparse. Data quality of the early seismic surveys conducted in the basin is poor, while the data quality of recent seismic surveys is good to excellent. To date, only regional gravity and aeromagnetic data cover the basin. Large parts of the onshore basin in both New South Wales and Queensland are currently under permit.

The only offshore seismic data are from the 1969 Yamba-Evans Head 2D seismic survey, that has a regional grid with an average 15 km line spacing. The NSW Department of Mineral Resources reprocessed these data in 2000/01, and the results were published in Alder (2001). They indicate the presence of a much more extensive sedimentary section offshore than was proposed in Wells and O'Brien (1994).

The first exploration for petroleum in the Nambour Basin is believed to be the drilling of two wells at Toorbul Point in 1887 or 1888 (Cranfield and Schwarzbock, 1976b). These wells are reported to have bottomed in granite at about 600 metres. Other deep exploration wells in the basin were Wellington Point Oil-1 (drilled in 1934), Winniells Pty Ltd-1 (1955), Cribb Island-1 (1960), Sandgate-1 (1963), St. Helena-1 (1968), and Matjara-1 (1968) that was located on an island in Moreton Bay. Several operators between 1964 and 1967 carried out limited gravimetric and seismic surveys (Cranfield and Schwarzbock, 1976b). The Queensland Department of Mines and Energy has also drilled some stratigraphic wells in the Nambour Basin. The offshore part of the Nambour Basin is very poorly known, with very limited data.

Bathymetry and elevation data for the Ipswich, Nambour and Clarence-Moreton Basins are shown in Figure 2. The basins all extend beneath a narrow continental shelf 30-100 km wide. It is not known whether any of the basins underlie the continental slope. Gravity data are inconclusive in delineating the basins (Figure 2). The Nambour Basin is too thin to be distinctive on gravity. Further south, the gravity character of the continental shelf appears to have greater similarity to the basement Beenleigh Block than to the onshore Ipswich/Clarence-Moreton Basins. The offshore extent of these basins is thus uncertain.

**Stratigraphy, Sequences and Tectonics**

The tectonic development of the Ipswich, Nambour and Clarence-Moreton Basins has been discussed by many workers, including Cranfield and Schwarzbock (1976a, 1976b), Harrington and Korsch (1985a), Korsch and others (1989), O'Brien and others (1994), Goscombe and Coxhead (1995), and Ingram and Robertson (1996). The following regional tectonic synopsis is from Korsch and others (1989), as depicted also in Figure 17.

1. Late Permian to Early Triassic oblique extension was controlled by transtensional strike-slip faults along the line of the present Esk Trough. Because of the sediment loading, a peripheral bulge developed on the hanging wall block and hence enhanced the elevation of the basement high (Gatton Arch). The footwall block (South Moreton Anticline) was also elevated.

2. In (?)Scythian to Carnian, transtensional basins developed both east of the South Moreton Anticline (site of the present Ipswich Basin) and west of the Esk Trough (Tarong Basin). Sedimentation in the Esk Trough accompanied thermal relaxation.

3. Cessation of oblique extension and commencement of thermal subsidence in the Carnian formed the Ipswich Basin, with deposition of Ipswich Coal Measures

through the Carnian possibly into the Norian. Little or no subsidence took place in the Esk Trough, because transpressional strike-slip faulting elevated the area.

4. In the Rhaetian, continued thermal relaxation saw sediments of the Clarence-Moreton Basin spread across rifts, basement highs and peripheral bulge alike. The rifts subsided faster than the basement highs and peripheral bulges because of increased sediment loading at the sites of extension.

The geographic locations of the Esk Trough and Tarong Basin are shown in Figure 16. These are regarded as discrete basins, with their own distinctive geological histories. They do not extend offshore, and are not considered further in this report.

The stratigraphy of the Nymboida, Ipswich and Clarence-Moreton Basins is summarised in Figure 18, after Willis (1994). The Nambour Basin has a single formation, the Landsborough Sandstone, which is of latest Triassic (Rhaetian) to Early Jurassic age (Day and others, 1983). It thus broadly correlates with the Woogaroo Subgroup and the overlying Gatton Sandstone of the Clarence-Moreton Basin. Events affecting and the broad palaeogeography of the stacked basin sequence are summarised in Figure 19.

**Nymboida Basin**

Further south, the relationship between the Ipswich and Clarence-Moreton Basins is shown diagrammatically in Figure 20, after Ingram and Robertson (1996). The oldest syn-rift rocks are of Middle Triassic age, and are partly equivalent in age to the Esk Trough sequence. They are known in outcrop as the Nymboida Coal Measures (see location on Figure 16) but are very poorly known under the main basin depocentres. These sediments have not traditionally been regarded as part of the Ipswich Basin, which was unconformably deposited over them after a hiatus. Goscombe and Coxhead (1995) use the term Nymboida Basin to describe this sequence, and we are adopting their usage in this report.

Early and Middle Triassic continental clastic and pyroclastics were deposited in NNW-trending graben. These sediments are best known from the Esk Trough sequence (Toogoolawah Group). These sediments occur in infra-basins now preserved beneath the Ipswich and Clarence-Moreton Basins. The Nymboida Basin is at least 1000 m and may be up to 2000 m thick (Willis, 1994; Figure 18), but it is entirely unknown whether or not it extends offshore under the continental shelf. It consists of continental clastics, volcanics and minor coal (Willis, 1994).

**Ipswich Basin**

Following a brief period of post-Nymboida Basin deformation with uplift and erosion, a tensional regime developed, which led to the development of the Ipswich and related coal basins. The Ipswich Basin consists entirely of coal measures, and is up to 1200 m thick. It is entirely Carnian (early Late Triassic) in age, and is normally described as an intermontane basin. It crops out over an area of about 4250 km$^2$ in southeast Queensland, but is believed to be much more extensive in subcrop in New South Wales (Ingram and Robertson, 1996; Figures 20, 21).

The oldest units include the Evans Head Coal Measures in New South Wales, and piedmont fan conglomerates of the Kholo Subgroup in southern Queensland. In the Nambour Basin area the sequence is mainly volcanic, represented by the Brisbane Tuff in the south and the North Arm Volcanics in the north. Equivalent volcanic-dominated rocks in the eastern Clarence-Moreton Basin are known as the Chillingham Volcanics. These rocks are conformably overlain by the main coal measures sequence, the late Carnian Brassall Subgroup, under the eastern Clarence-Moreton and southern Nambour Basin. This includes the Red Cliff Coal Measures in the southeast of the basin (Figure 16). Ipswich Basin sediments in the Brisbane area extend offshore under Moreton Bay (DRIQ, 1989), and possibly other offshore areas. Offshore New South Wales, the sedimentary sequence described by Alder (2001) may well belong to the Ipswich Basin, but these rocks have minimal age correlation – the only certainty being that they predate Cainozoic drape sediments.

In the middle of the Late Triassic, these Ipswich Basin sediments were affected by the final deformation of the New England Fold Belt post-orogenic transitional phase. This led to termination of sedimentation and high degrees of folding and faulting. Subsequent erosion of this surface produced the major unconformity (at the base of the Bundamba Group), which defines the base of the Clarence-Moreton Basin (Wells and O'Brien, 1994).

**Nambour Basin**

After a Norian hiatus, sediments of the Nambour Basin (in the northeast) and the Clarence-Moreton Basin were unconformably deposited on the eroded surface of the Ipswich Basin in the Rhaetian (latest Late Triassic). The western boundary of the Nambour Basin is bound by the Palaeozoic rocks of the D'Aguilar Block (to the northwest) and by the rocks of the Beenleigh Block (to the southwest). The eastern edge of the basin overlies Palaeozoic basement and the mid Triassic deposits of the Ipswich Basin. To the north the Nambour Basin grades into the Maryborough Basin.

The Nambour Basin consists of up to 600 metres of late Late Triassic (Rhaetian) to late Early Jurassic (Toarcian) sediments. Structures in the basin trend mainly north-northwest. The axis of the basin has this trend in the north but towards the south it becomes meridional. Neogene faulting formed a narrow north-northwest trending trough in the southern part of the basin. A subsidiary northerly plunging syncline is present between the Neogene faulting and the western margin of the basin (Cranfield and Schwarzbock, 1976b).

The depositional history of the Nambour Basin parallels that of the eastern half of the Clarence-Moreton Basin. A comparable suite of high-energy fluviatile quartzose sandstones and polymictic conglomerate was deposited on the eroded surface of the Ipswich Coal Measures during the Rhaetian. Overlying this is up to 120 metres of quartzose and sub-labile sandstone interbedded with siltstone, mudstone and minor coal deposited under less energetic fluviatile conditions. During the Early Jurassic up to 400 metres of fine to medium grained sub-labile to labile sandstones containing sporadic coarse pebbly sandstone bands and acritarch-bearing ferruginous oolite were deposited, under fluviatile and lacustrine conditions (Goscombe and Coxhead, 1995). Most of the Nambour Basin sediments are assigned to the Landsborough Formation, although there are some local names for units such as the Nambour Formation and Brighton Beds.

Onshore, the Nambour Basin underlies Neogene volcanics and fluvial sediments. Offshore, it is covered by Neogene marine clastics and some detrital carbonates. It also occurs under the barrier sand Moreton and Stradbroke Islands, and the muddy low islands of Moreton Bay.

**Clarence-Moreton Basin**

The Clarence-Moreton Basin was formed by crustal transtension originating from dextral strike-slip faults, which continued to deform the basin into the Cretaceous. The largest tectonic movements took place along the West Ipswich Fault and associated faults beneath the South Moreton Anticline. Significant movement also took place along the Coraki and Coast Range Faults, forming a complex pattern of highs and lows in the Logan Sub-basin. Smaller-scale movement in the west formed the Horrane Trough, initiating the Cecil Plains Sub-basin. Later movement along the South Moreton Anticline and Coraki and Coast Range Faults produced positive flower structures and thrusts with hanging wall anticlines in Clarence-Moreton sediments (Wells and O'Brien, 1994).

Onshore, the Clarence-Moreton Basin consists of about 3000 metres of Late Triassic to Late Jurassic sediments overlying the New England Fold Belt and Ipswich Basin sediments. The Clarence-Moreton Basin primarily formed from intracratonic sag that latter developed into a transtensional extensional regime. The New England Fold Belt sediments bound the Clarence-Moreton Basin in the north and south. To the west the Kumbarilla Ridge separates the Clarence-Moreton Basin from the Surat Basin, which is syndepositional in nature.

The Clarence-Moreton Basin can broadly be divided into three sub-basins: the Cecil Plains, Laidley and Logan Sub-basins (Figure 16). The Cecil Plains Sub-basin is a broad, relatively undeformed depression containing two sequences. The lower sequence consists of 2500 metres of sediments in a fault-bounded half graben, named the Horrane Trough (Wells and O'Brien, 1994; Figure 22). The second sequence consists of a relatively thin layer of sediments reaching a maximum thickness of 1300 metres. The Laidley Sub-basin consists of sediments that unconformably overlie the volcanic-dominated Toogoolawah Group, the fill of the Esk Trough. The sediments of the Laidley Sub-basin reach a maximum thickness of 1650 metres in the centre of the syncline (Figure 22). The sediments thin gradually onto the Gatton Arch to the west, and become abruptly thinner across the West Ipswich Fault and South Moreton Anticline to the east. The Logan Sub-basin is divided into two areas separated by a basement high, the Casino Trough and the Grafton Trough, with up to 4000 metres of sediments (Figure 22).

There also exists an offshore trough, the Yamba Trough, which may be an extension of the Logan Sub-basin (Figure 22). During 1969, the Yamba-Evans Head Seismic Survey provided 2D regional seismic coverage across the shelf area, adjacent to the southernmost portion of the onshore Clarence-Moreton Basin. This survey recognised a northeast trending, fault-bounded trough, known as the Yamba Trough.

In the latest-Late Triassic, vigorous erosion of uplifted basin margins initiated Clarence-Moreton Basin sedimentation with a widespread rapid influx of quartzose and quartz-lithic clastics. At this time, the Clarence-Moreton Basin sequence spread through the “Brisbane Straits” into the Nambour Basin and also across the Kumbarilla Ridge into the Surat Basin. However, at least part of the “Toowoomba arch” was still exposed at this time. This early sedimentation in the basin comprises proximal alluvial fan deposits of the Aberdare and Laytons Range conglomerates, followed by the mixed load fluvial sequence of the Raceview Formation. The latter comprises shale, siltstone and sandstone, which then gives way to a quartz sands-dominated sequence, the overlying Ripley Road/Precipice Sandstone units. General sediment transport directions at this time were from north to south and from west to east, at least in the southern parts of the basin (Wells and O’Brien, 1994).

The full extent of this widespread quartz and sand deposition was finally reached in the Early Jurassic with the covering of the last remaining parts of the Toowoomba arch. The maximum extent of the Clarence-Moreton Basin sedimentation was then established and continued deposition as represented by the Marburg Subgroup (Gatton Sandstone and Koukandowie Formation), which is equivalent to the Evergreen Formation and Hutton Sandstone of the Surat Basin. The Evergreen Formation was deposited in the Cecil Plains Sub-basin at this time and sedimentation was continuous with the Surat Basin across the Kumbarilla Ridge (Wells and O’Brien, 1994).

In mid-Jurassic times, the Walloon Coal Measures sequence became widespread in the Clarence-Moreton, Surat and Eromanga Basins. The Walloon sedimentation was terminated in the northern part of the basin by uplift and renewed erosion of basin margins. This led to quartz sands deposition represented by the Kangaroo Creek Sandstone. More lithic clastics from the south (Kumbarilla and Woodenbong beds) were deposited in the depocentres separated by the re-established “Toowoomba arch” (P.E. O’Brien, personal communication, 2004). Thus, the mid to Late Jurassic sequence lies conformably or unconformably on the Walloon Coal Measures in different parts of the basin (Wells and O’Brien, 1994).

The closing phases of sedimentation in the Clarence-Moreton Basin are represented by the Late Jurassic to Cretaceous Grafton Formation (in the axis of the Logan Sub-basin in NSW) and the Woodenbong and Kumbarilla Beds in Queensland. The final phase was the deposition of the Early Cretaceous Wallumbilla Formation in the Cecil Plains Sub-basin. During the Early Cretaceous, sedimentation ceased and widespread erosion occurred due to regional uplift. The erosion which has continued, more or less uninterrupted, to the present day has defined the shape and limits of the Clarence Moreton Basin. Uplift culminated in the Late Cretaceous with the initiation of sea-floor spreading and the formation of the Tasman Sea. Basaltic vulcanism was initiated in the mid-Cainozoic under a regime of gradually increasing regional tensional stress (Wells and O’Brien, 1994).

Recent interpretation of the reprocessed Yamba-Evans Head Seismic Survey by the New South Wales Department of Mineral Resources has indicated that a much more widespread shelfal cover of sediments exist in the offshore area (Alder, 2001). The reprocessed seismic data indicates a total shelf sediment thickness of up to 2.0 seconds (two-way-time, approx. 2500 metres) extending across much of the outer shelf. Figure 27 shows an example of these data from seismic Line MA-05. An interpretation of this line appears in Alder (2001).

The sediment cover across the shelf comprises of a number of distinct packages. The uppermost packages are correlated with prograding sediment wedges, which are identified elsewhere as Cainozoic ‘post-breakup’ deposits related to Tasman Sea margin development. These packages are distinguished from underlying sediments that show stronger structural control (faulting and tilting). These overlie a deeper zone interpreted as economic basement. The architecture of the deeper sediments is consistent with deposition prior to the sag, or post-breakup, phase of Tasman margin development. If these deeper sediments are intracratonic in origin they may belong to either the Clarence-Moreton or Ipswich Basin sequences (Alder, 2001).

**Potential Source Rocks**

Potential source rocks exist in the Nymboida, Ipswich and Clarence-Moreton Basins, but not in the Nambour Basin. Source potential is summarised in Figure 23.

Continental clastics and volcanics dominate the Nymboida Coal Measures, but coals in the sequence have some potential to source dry gas. The sequence is overmature for liquids generation (Willis, 1985).

Potential source rocks appear to be present in the Ipswich Basin. Vitrinite reflectance measurements of coal seams in the Ipswich area range from 0.89 to 1.29%. Thermal Alteration Index (TAI) values for the Ipswich Coal Measures are in the general range of 2.3 to 3.0+ (Helby and Partridge, 1979) and there appears to be a general increase in values across the basin from west to east. The highest value was reported in the eastern side of the basin in the offshore well APS Matjara-1 (positioned east of North Stradbroke Island). Herbaceous and woody types dominate the kerogen types, and the sequence is more likely to generate gas than oil. Willis (1985) considered the Ipswich Coal Measures to have good source rock potential, with high TOC contents, but also thought that their high-maturation state and dominantly humic kerogen contents favour generation of gas.

Willis (1985) summarised the source rock potential within the Clarence-Moreton Basin. The Bundamba Group is mature for the generation of gas, but has low TOC contents, and consequently has a poor source rock potential. The Marburg Formation is mature for oil and gas generation, with moderate contents of sapropelic organic material, but variable (low to high) TOC contents, and has fair prospects as a local source for gas and possibly oil. The Walloon Coal Measures have source rock characteristics favourable for the generation of liquid hydrocarbons: generally high TOC, comparatively high proportion of sapropelic organic matter, and maturation states compatible with oil generation (Willis, 1985).

Powell and others (1993) and O’Brien and others (1994) also examined the source rock potential of the Clarence-Moreton Basin in some detail. Several formations were evaluated for kerogen type based upon hydrogen and oxygen indices, according to Tmax and basin position (Figure 24). O’Brien and others (1994) also produced regional maturation maps for the Walloon Coal Measures, Koukandowie Formation and Raceview Formation (Figure 25). These show marked regional variations in maturation levels. As would be expected, the deeper stratigraphic units show higher levels of maturation, but it is notable that the zone of oil generation is further west in each deeper unit. Potential source rocks adjacent to the southern coast are all currently beyond the oil window (Figure 25). It would not be wise to write off the potential of the offshore section on this basis however, as higher heat flows in the area might actually bring the relatively thin offshore sequence into the oil window. At a maximum thickness of about 2500 metres (Alder, 2001), it might otherwise be expected to be thermally immature.

The Nambour Basin appears to lack adequate source rocks. Thin coal and carbonaceous shale bands are present within the Landsborough Sandstone to a limited extent. Vitrinite reflectance of a thin coal band near the top of the Landsborough Sandstone was measured by the Department of Resource Industries Queensland (1989) at 1.28. Hawkins (1984) reviewed source-rock sampling undertaken in the basin. Thermal Alteration Index values from the Nambour basin sequence, intersected in petroleum exploration wells and departmental stratigraphic bores range from 2.1 to 2.5 (Helby and Partridge, 1979). These maturity data indicate that the Nambour Basin sequence was more deeply buried at some time in the past, and that any possible source rocks could have generated hydrocarbons. However, if such source rocks were ever present they have subsequently been removed by erosion.

**Potential Reservoirs, Seals and Trap Types**

Clastic rocks within the Nymboida Basin include sandstones and conglomerates, which could form reservoirs, but reservoir quality is probably low due to diagenesis and the presence of volcaniclastic detritus. A gas show in the Nymboida Coal Measures was recorded in the Sextonville-1 well in the central basin area. Any Nymboida Coal Measures reservoirs would require intraformational seals. It is also possible that the overlying Chillingham Volcanics could form a regional seal in the central basin area.

Reservoir sandstones are generally lacking in the Ipswich Basin (Cranfield and Schwarzbock, 1976a). Sandstones are lenticular, mostly lithic and commonly are interbedded with siltstone and mudstone (Mengel, 1976). Sandstones of the Ipswich Coal Measures intersected in GSQ Ipswich 26 commonly contain secondary calcite cement (Almond, 1982); wireline logs run in this bore indicate a general lack of reservoir potential.

In the Nambour Basin, the lower part of the Landsborough Sandstone, previously known as the Woogaroo Subgroup, appears to be suitable as a reservoir. Sandstones are sub-labile to quartzose and have better reservoir potential than sandstones in the upper part of the unit. This upper part, previously referred to as the Marburg Formation, is more labile and the porosities of the sandstones are lower. In isolated areas the visible porosity of the upper part is estimated to range from 0-13% (Green and Armstrong, 1986). Reservoir potential of the basin offshore is unknown.

Seals are absent onshore in the Nambour Basin. The only possible exceptions are areas of Neogene volcanics in the north of the basin, which could locally seal Landsborough Sandstone reservoirs. However, this part of the basin overlies Gympie Block basement, and thus lacks underlying source rocks, and long distance lateral migration from the south is not feasible due to the absence of seal. In the offshore area, Cainozoic shelf clastics and carbonates could theoretically form an effective regional seal over potential Nambour Basin reservoirs.

The Clarence-Moreton Basin contains a number of potential reservoir units. The basal Laytons Range Conglomerate could form reservoirs, but lacks any effective seal. The overlying Raceview Formation has not generally been considered as a potential reservoir, but quartzose sandstones are present. The best reservoir characteristics were found in fining-upward fluvial channel deposits, which also contained residual oil (O'Brien and others, 1994). In Ropely-1, drilled in the Laidley Sub-basin, the Raceview Formartion had porosities of up to 15% and permeabilities of 2860 md (Webby, 1984; O'Brien and others, 1994). Reservoir characteristics of much of the Raceview Formation are however poor due to its overall muddy and silty character. Intraformational flood plain shales would seal any reservoirs within this unit.

The Ripley Road Sandstone is the most extensive potential reservoir in the Clarence-Moreton Basin, with excellent porosity and permeability encountered in many holes, and indications of hydrocarbons in wells such as Tullymorgan-1 (Ties and others, 1985). It shows a general decrease in porosity from west to east, attaining maximum permeabilities of around 2000 md in the Cecil Plains Sub-basin, compared to a maximum of 59 md from one of the few cores in the Logan Sub-basin (Thompson, 1987; O'Brien and others, 1994).

The basal Calamia Member of the Gatton Sandstone may provide a regional seal for the underlying Ripley Road Sandstone. The Gatton Sandstone as a whole is typically impermeable because of its high labile-grain content (O'Brien and Wells, 1994), and is regarded as a poor quality reservoir. However, some wells encountered quartzose sandstones in the top of the Gatton Sandstone with good porosity and permeability. Cores from BMR Warwick-7 had porosities of up to 25.9% and permeabilities of 961 md (Wells and others, 1990). These scattered sandstone bodies could be top-sealed by extensive flood plain shales of the Ma Ma Creek Member of the Koukandowie Formation (O'Brien and others, 1994).

The Koukandowie Formation also contains the Heifer Creek Sandstone Member, which has good porosity and permeability in granule conglomerates and coarse sandstones at the base of fining-up channel fills (O'Brien and others, 1994). This reservoir unit produced the best gas flows to date in the Clarence-Moreton Basin, in the Clifden-2 and Horgarth-2 wells. The latter well flowed gas at 14,000 $m^3$/day (Powell and others, 1993). At both locations the Heifer Creek Sandstone Member reservoir showed good porosity but poor permeability, and the gas fields were deemed to be uneconomic (Cadman and others, 1998). The Heifer Creek Sandstone Member is thinner and less porous in the Logan Sub-basin than in the Laidley and Cecil Plains Sub-basins. However, seal of this reservoir unit depends upon the presence of overlying suitable flood plain facies within the Koukandowie Formation, which is more likely in the Logan Sub-basin than elsewhere (O'Brien and others, 1994). Other coarse sandstone bodies within the Koukandowie Formation could also form reservoirs, and would rely upon intraformational seal.

Sandstones within the Walloon Coal Measures are volcanogenic, and have had porosity destroyed by diagenesis and grain compaction. Even so, the Kyogle-1 well encountered a sandstone body that produced water to the surface, suggesting that secondary targets may be present. Any porous and permeable sandstone bodies within the Walloon Coal Measures could be sealed by the typical, high-labile sandstones of the Walloons as well as by fine-grained facies (O'Brien and others, 1994).

The Kangaroo Creek Sandstone is a sheet of interconnected quartzose sandstone bodies deposited by braided streams (Wells and O'Brien, 1994). It has good reservoir qualities, but outcrops extensively and lacks seal in the onshore basin, as does the overlying Grafton Formation. Offshore, Cainozoic sediments may provide seal for both of these formations (Alder, 2001).

Ties and others (1985) and O'Brien and others (1994) recognised four styles of potential trap types in the Clarence-Moreton Basin:

i. *Drape over sub-Clarence-Moreton topography*. Ties and others (1985) identified several large drape features at Ripley Road Sandstone and Koukandowie Formation levels. These traps rely on seals and reservoirs extending across the culminations of the drape features.

ii. *Reservoir pinch-outs against sub-Clarence-Moreton topography*. Raceview Formation and Ripley Road Sandstone reservoirs may pinch-out against basement highs such as the Central Platform (Figure 21). Such traps require an effective top seal overlapping the reservoir sandstone (O'Brien and others, 1994).

*iii.* *Hanging wall anticlines on minor thrusts.* Most of the inferred strike-slip faults in the basin exhibit positive flower structures on restraining bends or thrusts in zones of transpression. These thrusts are arcuate and consequently provide four-way dip closure at some levels (Wells and O'Brien, 1994).

*iv.* *Stratigraphic traps.* Facies variations are likely to play a major part in any style of entrapment in the Clarence-Moreton Basin because of the lateral variation of the sediments (O'Brien and others, 1994). Ties and others (1985) suggested that facies changes caused the entrapment of gas at the Horgarth field, on what is a plunging anticline lacking four-way dip closure.

Because of the non-continuous nature of the sandstone bodies in the sedimentary section, it is unlikely that long-range migration of hydrocarbons has occurred. The maximum limit of migration is probably about 10 km to as much as 15 km (Ingram and Robinson, 1996).

In addition to the above trap styles, other as yet unrecognised trap types may be present offshore. Alder (2001) suggested that the potential juxtaposition of Cainozoic cover overlying an offshore extension of the Clarence-Moreton Basin provides opportunities for top seal and Cainozoic trapping mechanisms which appear to have no parallel onshore. However, we suggest that the timing of any petroleum generation from the offshore basin extension is likely to predate the deposition of Cainozoic cover. Any possible reservoirs within the offshore section would therefore require intraformational seals.

## Maturity and Timing

Timing of major events in the Nymboida, Ipswich, Nambour and Clarence-Moreton Basins is summarised in Figure 19. As described above, both the Nymboida Basin and Ipswich Basin sediments are generally overmature for oil generation. The exception to this is in the relatively thin Cecil Plains Sub-basin, where the Ipswich Coal Measures are currently in the oil window (Russell, 1994). The Nymboida Coal Measures would only be generating dry gas at present, but the Ipswich Coal Measures are probably generating condensate as well as dry gas. In the central Clarence-Moreton Basin, modelling by Russell (1994) suggested that the basal Ipswich Coal Measures entered the oil window in the Early Jurassic, and that any *in situ* oil generated would have been converted to gas by cracking by the mid-Cretaceous. Ipswich Basin oil generation thus predates the main period of trap formation in the overlying Clarence-Moreton Basin. However, large quantities of gas have probably been generated in both the Nymboida and Ipswich Basins through time. The most likely migration route for the gas would be via fractures and faults into overlying reservoirs (Ingram and Robinson, 1996).

Between 1.5 km and 3 km of sediment has probably been removed from the Clarence-Moreton Basin by erosion, with greater thicknesses eroded in the east and south of the basin (Russell, 1994). The systematic increase from west to east in thermal maturity of the sediments of the basin indicates that the eastern part of the basin has been subjected to greater depth of burial and/or higher heat flows than the western part (Powell and others, 1993; Figure 25). The major period of folding in the Clarence-Moreton Basin occurred in the mid-Cretaceous. The maximum palaeotemperatures were reached in mid-to-Late Cretaceous time. At this time principle structural traps were in place (O'Brien and others, 1994). However, there are problems with the geometry of source kitchens and traps, as traps in the zone mature for oil are actually receiving gas from deeper in the section, making oil accumulations unlikely (P.E. O'Brien, personal communication, 2004).

For potential source rocks within the Clarence-Moreton Basin, fission-track data and maturation modelling shows that hydrocarbons were generated in the period 100 to 80 Ma. This was the time of maximum depth of burial and maximum heat flow (Powell and others, 1993). Generation from Clarence-Moreton Basin sources thus postdates the mid-Cretaceous folding that is the principal cause of structural trap formation in the basin.

The age of the offshore sequence is unknown, as is its heat flow history, so any issues of maturity and timing are purely speculative. We know that a potential regional seal of continental shelf and slope, clastic and carbonate drape sediments was deposited from the early Palaeogene onwards, but this was probably long after any possible petroleum generation occurred in the older section.

## Key Unknowns

The Clarence-Moreton Basin has been lightly explored. Many large areas have never been surveyed using seismic techniques or been subjected to anything but shallow coal exploration drill-holes. Large areas with exploration potential have never been drilled. The only two wells drilled to date on well-established structural closures are

Rappville-1 and Tullymorgan-1. The remaining wells were drilled on structures with inadequate seismic control and with doubtful closures.

Source rock analyses and exploration results to date suggest that the most likely conventional hydrocarbon to be found will be gas, particularly from Nymboida and Ipswich Basin sources, but Clarence-Moreton Basin sourced oil accumulations are also possible (Figure 23). The problem is that traps in the zone mature for oil are actually receiving gas from deeper in the section, making oil accumulations unlikely (P.E. O'Brien, personal communication, 2004). Minimal studies have been done on reservoir quality in the Clarence-Moreton Basin. Only a few unpublished studies have been done on sandstone diagenesis and porosity. Further detailed reservoir studies would enable a greater understanding of potential petroleum targets.

The greatest unknown is the age and geological affinity of the offshore sedimentary sequence east of the southern Clarence-Moreton Basin. If these are Ipswich (or possibly even Nymboida) Basin equivalents the likelihood is that any potential source rocks would be gas-prone. If they are Clarence-Moreton Basin equivalents then the possibility of oil accumulations can not be dismissed, although high heat flows in the eastern Clarence-Moreton Basin suggest that the offshore section might be more likely to currently contain only gas.

Alder (2001) also proposed another alternative. If the deeper sediments were deposited during the Tasman margin syn-rift phase then their prospectivity might be more analogous to that of the Gippsland Basin. In this scenario the offshore sequence belongs to a totally separate and previously unrecognised basin. The quantity of sediments observed on seismic data could easily have been derived from the unroofed Clarence-Moreton Basin to the west, during the Late Cretaceous.

**Environmental Sensitivities**

The offshore Nambour, Ipswich and Clarence-Moreton Basins underlie whale migration paths between May and October. Parts of the offshore Clarence-Moreton Basin may underlie the Solitary Islands Marine Park and Reserve if the offshore sedimentary sequence extends this far south.

The coastal area is also extensively settled, including residential and tourist areas of the Sunshine Coast between Caloundra and Noosa Heads, so some sensitivity to near-shore exploration activities could be expected. Major shipping routes also pass through the area, and the Moreton Bay area is heavily utilised for recreational boating and fishing.

Onshore there are a large number of National Parks, and several offshore islands in the Moreton Bay area are either wholly or in part National Parks. The heavily settled greater Brisbane metropolitan area covers a large part of the Nambour and exposed Ipswich Basin area.

## Conclusions

The Nymboida Basin is overmature for oil and currently generating only dry gas. It is most unlikely to contain suitable reservoirs due to its depth of burial and heat flow history, as diagenesis will have destroyed any primary porosity or permeability.

Oil prospects for the Ipswich Basin are poor. The kerogen types present indicate that the rocks are more gas-prone than oil-prone. Any Ipswich Basin oil generation would also predate the main period of trap formation in the overlying Clarence-Moreton Basin, but it may source gas for that basin. The Ipswich Basin also has potential as a source of coal-seam methane.

Prospects for the discovery of hydrocarbons in the Nambour Basin are poor. The reservoir potential of the Landsborough Sandstone is good, but it crops out extensively and lacks a suitable seal. While the basin sequence is within the oil window, source material is very limited. The Ipswich Basin underlies part of the southern Nambour Basin and could be a source of gas, but the only possible traps would be offshore, where Cainozoic marine sediments have the potential to act as a regional seal.

O'Brien and others (1994) evaluated the petroleum prospectivity of the onshore Clarence-Moreton Basin, and divided it into six areas on the basis of level and type of prospectivity (Figure 26). Their conclusions are as follows:

1. The Cecil Plains Sub-basin has very poor prospectivity because of low thermal maturity.
2. The Laidley Sub-basin has some minor potential for oil or gas discoveries in the Raceview Formation.
3. The area along the State border has very poor potential because of extensive intrusion by Cainozoic igneous rocks and thick basalt cover.
4. The northern Logan Sub-basin has some potential for oil and gas in the Raceview Formation, Ripley Road Sandstone and Koukandowie Formation, although data are scarce. The underlying Ipswich Coal Measures may also have some gas potential.
5. Most of the southern Logan Sub-basin has potential for gas discoveries throughout the basin section.
6. The western side of the southern Logan Sub-basin has minor potential for small oil accumulations, in addition to gas potential.

The offshore Yamba Trough falls into Area 5 of O'Brien and others (1994), and thus is likely to have gas potential. The prospectivity of the more extensive offshore sequence identified by Alder (2001) is unknown, because the age, geohistory and nature of the sediments therein are all unknown. For that reason, its potential prospectivity for petroleum can not be discounted, and it is possibly prospective for both oil and gas.

## *Maryborough Basin*

### Overview

The Maryborough Basin straddles the southeast Queensland coast in the Bundaberg-Fraser Island-Noosa Heads area (Figure 28), and covers an area of approximately 9,100 $km^2$ onshore (Lipski, 2000) and at least 15,000 $km^2$ offshore (Hill, 1994). The offshore part of the basin is known only from geophysical data, but the onshore basin is well known from outcrop, and also has been intersected by four petroleum exploration wells and several stratigraphic holes. The Maryborough Basin is a deep NNW trending synclinal structure, and contains a thick sequence of up to 10 km of sediments (and some volcanics) of latest Triassic to Early Cretaceous age (Ellis, 1966; Ellis and Whitaker, 1976). The basin developed between the earliest Triassic and mid-Jurassic as an epicontinental downwarp, probably a foreland depression. Neocomian volcanism and rifting led to a second phase of deposition, before basin inversion in the mid-Cretaceous produced major folding and faulting (Hill, 1994). Subsequent uplift and erosion led to the loss of several km of section from much of the Maryborough Basin, particularly onshore. The latest Triassic to Middle Jurassic sedimentary succession consists of fluvial sandstone overlain by fluvio-lacustrine coal measures. Over most of the basin these are unconformably overlain by Late Jurassic volcanic flows and pyroclastics, which are in turn overlain by up to 5 km of Cretaceous deltaic to marine sediments. Several kilometres of section were probably lost to Late Cretaceous erosion. Offshore, up to 1.5 km of Cainozoic marine sediments overlie the Maryborough Basin proper. The available evidence suggests that the Maryborough Basin has significant gas potential, but that the presence of economic oil accumulations is more problematical.

### Current State of Knowledge

Exploration for oil in the Maryborough Basin started in the 1920's with the drilling of three shallow wells by the Isis Petroleum Prospecting Syndicate. All three of the wells were dry with the deepest of the three wells being Elliot River-1, which reached a depth of approximately 180 metres.

During the 1950's the Lucky Strike Drilling Company carried out surface mapping to delineate drilling prospects. As a result the Cherwell Creek-1 and Susan River-1 exploration wells were drilled in 1954 and 1955 respectively (locations on Figure 28). Both wells reached depths greater than 2400 metres but were dry; they were however drilled without gas detection equipment, and both were later found to have been drilled off-structure (Derrington, 1981; Lipski, 2000). Further geophysical mapping and reflection seismic surveying were carried out before Lucky Strike Drilling Company relinquished the area in 1959.

Pacific American Oil Company then obtained the exploration rights over much of the basin in 1959, and explored the area with various other companies up to 1968. Photogeological interpretation was undertaken in 1961, aeromagnetic surveying in 1962, and field mapping and gravity surveys in 1963. Onshore and offshore seismic surveys were also carried out (Namco, 1968; Bruce and Thomas, 1964; Shell, 1965). Data from offshore seismic surveys shot in the early 1960s are of poor quality, but data from those shot towards the end of the decade are more useful (Hill, 1994). One exploration well was drilled in 1966/67, Gregory River-1, which produced the only hydrocarbon show in the basin to date (location on Figure 28). Gregory River-1 flowed over 5,000 $m^3$/day of gas (mainly methane) from the lower sandy part of the Maryborough Formation (Shell, 1968).

Universal Energy Pty Ltd drilled the Gregory River-2 well in 1981 after a farm-out (location on Figure 28). Trace amounts of gas were produced from the Burrum Coal Measures and the Maryborough Formation at rates too small to measure, due to poor porosity and permeability (Derrington, 1981).

In 1989 AGSO Survey 91 investigated the structure, stratigraphy and evolution of the Maryborough, Capricorn and northern Tasman Basins. About 1450 line-km of seismic data was collected over the offshore Maryborough Basin, in particular over Hervey Bay and the continental shelf southeast of Fraser Island (Hill, 1994; Figure 29). Up to 5 km of Early Cretaceous sediments are preserved in a NNW-trending syncline beneath the western side of Hervey Bay, and depth to basement might be as much as 10 km (Hill, 1994). Survey 91 also established that the Maryborough Basin extends beneath the continental shelf southeast of Fraser Island. The section is folded and faulted, with broad anticlinal structures present (Hill, 1994).

Part of the onshore Maryborough Basin is currently under permit to Magellan Petroleum Australia Limited as ATP 613P. Magellan undertook a seismic survey within their permit in 1998 (Magellan, 1999). In 2003 Magellan drilled the Gregory River-3 appraisal well, which was plugged and abandoned. No detailed information on the results of this well has yet been released by the operator.

**Stratigraphy, Sequences and Tectonics**

The oldest known rocks in the vicinity of the Maryborough Basin are Silurian to Early Carboniferous sediments of the Yarrol Trough to the northeast (Hill and Maxwell, 1967). During the Middle Carboniferous the area was metamorphosed and uplifted. Renewed subsidence in the Early Permian led to the deposition of the Gympie Basin sequence, in moderate to deep marine environments, with local submarine vulcanism (Figure 30). During the Early Triassic the Gympie Basin sedimentation became more fluvial, before marine conditions returned with uplift and metamorphism (Ellis, 1968). This uplift and metamorphism was probably associated with movement along major NNW-SSE trending fault zones, such as the Electra Fault Zone that forms the western boundary of the Maryborough Basin. Also associated with this uplift was a series of andesitic volcanism and granitic/gabbroic intrusions (Ellis, 1968).

Sedimentation in the Maryborough Basin commenced during the Late Triassic, with the deposition of the thick, fluvial Myrtle Creek Sandstone (Figures 30, 31). Ellis (1968) described this unit as being composed entirely of orthoquartzite and quartzose sandstone, but drilling in the Gundiah Embayment in the southwest of the basin showed that this was true only of the upper Myrtle Creek Sandstone, and that the lower parts of the unit comprised interbedded sandstone, siltstone and shale (Cranfield, 1993). This is important in considerations of hydrocarbon source potential. The Myrtle Creek Sandstone is conformably overlain by an Early Jurassic coal measure sequence, the Tiaro Coal Measures. This unit consists of shale, mudstone, siltstone, sandstone, coal, volcanics and some limestone (Ellis, 1968). A thin oolite-rich section forms a prominent marker bed within the Tiaro Coal Measures (Cranfield, 1993). Together the Myrtle Creek Sandstone and the Tiaro Coal Measures form the Duckinwilla Group (Cranfield, 1993). Interpreted environments of deposition for the Duckinwilla Group range from fluvial upper plain, through fluvial lower plain, to fluvio-lacustrine (Figures 30, 31).

Uplift in the Late Jurassic was followed by transtensional rifting and volcanism in the earliest Cretaceous (Hill, 1994; Figure 32). This volcanic episode is represented by intermediate to acid flows, pyroclastics, tuffaceous sandstone and siltstone of the Grahams Creek Formation, which unconformably overlies the Duckinwilla Group (Figures 30, 31). Also at this time, sills and dykes intruded into the previously deposited formations in the westerly half of the basin. The Grahams Creek Formation appears to have in-filled half-graben formed by previous block faulting and contemporaneous transtensional rifting (Hill, 1994; Figures 31, 32). It is absent from western parts of the basin, such as the Gundiah Embayment (Cranfield, 1982), and from Fraser Island in the east (Grimes, 1982). Radiometric (K-Ar) dating of an andesite flow near Maryborough gave an age of 140 ± 5 Ma for that part of the Grahams Creek Formation (Cranfield, 1993).

Thermal relaxation and sediment loading in the middle Cretaceous initiated the resumption of clastic sediment accumulation in the Aptian (Figure 32). The Maryborough Formation comprises mudstone, shale, siltstone and sandstone with minor conglomerate, waterlaid tuff, coal and dense limestone (Cranfield, 1993). It unconformably overlies the Tiaro Coal Measures in the Gundiah Embayment, and the Grahams Creek Formation where that unit is present. A basal conglomerate composed largely of reworked Grahams Creek volcanic detritus is common in the latter areas (Ellis, 1968). The Maryborough Formation appears to thicken from about 600 m in the south, to over 2.4 km in the north (Benbow, 1980). Its basal part may also be slightly older in the east than in the west: late Neocomian in the Susan River area compared to Aptian in the Gundiah Embayment (Cranfield, 1993). Interpreted environments of deposition for the Maryborough Formation are predominantly marine shelf to coastal (Figure 30).

The Maryborough Formation was subdivided into several members on the basis of the section encountered in the Gregory River-1 and Gregory River-2 wells (Derrington, 1981, Figure 33). It is not known how valid this subdivision is throughout the Maryborough Basin, but the basal Gregory Sandstone Member and overlying Cherwell Mudstone Member appear to be widely distributed in at least the north (Figure 33)

In the east of the basin, the Maryborough Formation is conformably overlain by the Albian Burrum Coal Measures. This formation is restricted to a flat coastal belt 80 km long and 28 km wide (Cranfield, 1993). The Burrum Coal Measures are subdivided into three informal members. The lower and upper 'unproductive' members contain mainly intercalated sandstones and siltstones with minor shale, conglomerate and no economic coal seams. The middle 'productive' member contains mainly shale with thin coal seams, minor siltstone and rare sandstone (Cranfield, 1993). Fielding (1992) proposed a lower delta plain environment of deposition for the 'lower unproductive' member, and a middle-upper delta plain setting for the 'middle productive' member.

The thickness of the Burrum Coal Measures is variable throughout the basin (Cranfield, 1993), and estimates of maximum thickness range from 2.4 km (Benbow, 1980) to over 3 km (Ellis, 1968), and over 3 km for the 'lower unproductive' and part of the productive' members only in part of the Bundaberg 1:250 000 map sheet area (Ellis and Whitaker, 1976). Hill (1994) thought the average thickness of the Burrum Coal Measures was about 1.7 km, which agrees with the estimate of Siller (1961). The combined thickness of the Maryborough Formation and Burrum Coal Measures under Hervey Bay is some 5 km, of a total sediment thickness for the basin in this area of 9-10 km (Hill, 1994). The Maryborough Formation/Burrum Coal Measures section under Hervey Bay occurs in a deep, faulted synclinal structure, which also extends under Wide Bay, to the south of Fraser Island (Hill, 1994).

It is probable that sedimentation in the Maryborough Basin continued after the Albian, but if so no early Late Cretaceous sediments have been preserved onshore, and the offshore section has not been drilled. Late Cretaceous inversion in the Maryborough Basin produced a number of northwest-trending asymmetrical anticlines and synclines, with both high angle and low angle reverse faults (Lipski, 2001). This major tectonic compression event also affected the Surat and Eromanga Basins, and is known as the Winton Movement; it has been dated at 85-80 Ma (Lipski, 2001). In the Maryborough Basin the Winton Movement was transpressional in nature, and resulted in widespread uplift and subsequent erosion as well as folding (Figure 32). Several kilometres of Maryborough Basin section has been removed by erosion (Hill, 1994), most of which probably occurred in the Late Cretaceous.

Seafloor spreading in the northernmost Tasman Basin commenced at 63 Ma (Hill, 1994). The eastern conjugate margin to the Maryborough Basin margin is the poorly known Kenn Plateau. The limited data available suggest that the Kenn Plateau area has a syn-rift sequence at least 2 km thick, overlain by a post-breakup sequence no more than 1 km thick (Hill, 1994). The syn-rift sequence probably consists of clastic rocks derived from the upper, eroded and now missing Maryborough Basin section, whilst the younger sequence is almost certainly made up of pelagic carbonates, as is the case on the Lord Howe Rise further south. Offshore, southeast of Fraser Island, a wedge of mainly Neogene shelfal sediments overlies a seaward-dipping, erosionally-truncated platform of mainly Maryborough Basin rocks (Hill, 1994). The apparent absence of syn-rift sediments here is consistent with the asymmetrical nature of the Tasman Sea rift further south. Cainozoic products of Maryborough Basin erosion now mainly lie at the base of the continental slope in the adjacent northern Tasman Basin, where post-breakup deposits alone are typically 3.5 km thick (Hill, 1994).

A number of small, Eocene graben, often containing oil shale and other lacustrine rocks, formed in south-east Queensland (Day and others, 1983). One of these, the Bundaberg Trough, formed in the northern Maryborough Basin. Here, 45 m of olivine-rich Pemberton Grange Basalt is overlain by nearly 100 m of late Early Eocene fluvial sand, gravel, clay, shale and brown coal - the Fairymead beds (Day and others, 1983).

More widespread fluvial sedimentation occurred across the onshore Maryborough Basin in the Late Eocene to Early Miocene. Up to 50 m of quartzose sandstone, siltstone, with minor conglomerate, mudstone and shale form the Elliot Formation. The thin, colluvial Takura beds near the basin margins are facies equivalents of the

Elliott Formation (Day and others, 1983), as are postulated fluvio-deltaic sediments of this age under Hervey Bay (Hill, 1994).

Southeast of Fraser Island, an early Oligocene unconformity separates the Maryborough Basin section proper from younger shelf deposits. These younger deposits range from a few tens of metres thick near the coast, to up to 1600 m thick at the shelf edge (Hill, 1994).

**Potential Source Rocks**

The oldest potential source rocks in the Maryborough Basin are intraformational black shales in the lower part of the Myrtle Creek Sandstone (Lipski, 2000). Shales and coals in the overlying Tiaro Coal Measures also have source potential. Both these formations are known only from outcrop and shallow stratigraphic drilling near the basin margins, so there are no data on their geochemical characteristics in the central basin. They are however currently overmature for liquid hydrocarbons and well into the dry gas window (Figure 34).

The main potential source rocks of the Maryborough Basin are shales of the Maryborough Formation, and shales and coals of the overlying Burrum Coal Measures where they are present. The organic material analysed to date from this Cretaceous section is of non-marine origin, comprises both Type II and Type III kerogens, and is both oil and gas prone (Lipski, 2000). Although the Maryborough Formation includes marginal marine and estuarine facies (Cranfield, 1993), these source rocks were probably already into the gas window at the main time of trap formation (Lipski, 2001). The best source rocks within the Maryborough Formation are probably marine black shales in the lower part of the unit.

**Potential Reservoirs, Seals and Trap Types**

The oldest potential reservoir unit in the basin is the Myrtle Creek Sandstone. This is very deeply buried in the central basin, and is likely to be tight. Near the basin margins porosities of up to 30% have been observed in outcrop with good permeability, but some of these favourable reservoir characteristics may have been induced by surface leaching (Lipski, 2001). An exploration fairway may exist on terraces parallel to the basin margins, where the unit may not have experienced prohibitive depth of burial; there is also potential for fracture porosity (Lipski, 2001). Any Myrtle Creek Sandstone reservoirs would be sealed by intraformational shales. Trap integrity is likely to be a problem however, particularly near the basin margins. Structural traps formed by Jurassic block faulting are likely to have been breached by subsequent Late Cretaceous compression and folding (Figures 31, 32).

The main reservoir target in the Maryborough Basin is the Gregory Sandstone Member of the Maryborough Formation (Lipski, 2001). This unit flowed gas at a rate of up to 200 million cubic feet per day in when tested in the Gregory River-1 well. One 27 metre interval was tested from a gross hydrocarbon bearing interval of over 500 metres. Wireline log evaluation from this well indicates that porosities average 6%, but increase to 10-12% in several thin untested zones (Lipski, 2001). Matrix permeability is generally low in the limited core samples from Gregory River-1, but numerous fractures were observed in core, some bubbling gas (Shell, 1967). There is also reservoir potential in the Upper Sandy Member of the Maryborough Formation (Lipski, 2001). Intraformational shales within the Gregory Sandstone Member and Upper Sandy Member should seal numerous prospective thin sandstones, whilst the top of the Gregory Sandstone Member should be adequately sealed by thick carbonaceous shale in the Cherwell Mudstone Member (Lipski, 2001; Figure 35).

Offshore, reservoirs and/or seals could possibly be present in equivalents of the Elliott Formation, but this play type is hypothetical given the absence of offshore well data.

The dominant trapping style in the Maryborough Basin is structural, with all potential structural traps identified to date related to Late Cretaceous transpressional deformation. This resulted in a number of northwest-trending asymmetrical anticlines and fault-bounded rollovers (Lipski, 2001). This transpressional event overprinted a structural style that was mainly extensional through most of the basin's history, and in many cases inversion structures were generated by reactivation of pre-existing normal faults (Lipski, 2001).

### Maturity and Timing

The Upper Triassic to Lower Jurassic Duckinwilla Group is currently well into the dry gas window. Indeed, maturation modelling from the central basin suggests that the Tiaro Coal Measures source unit had expelled close to 100% of generated gas by the Santonian inversion event that formed known structural traps (Lipski, 2001). This implies that gas generated from this source was available only for remigration from earlier formed traps that were either breached or rearranged at that time (Lipski, 2001). It is possible though that Duckinwilla Group sources nearer the basin margins may still have been generating gas after Santonian trap formation.

Similar modelling of Maryborough Formation source units from the central basin suggests that they had expelled only 60-80% of generated hydrocarbons by the time of trap formation, allowing for continued charging during and after trap formation (Lipski, 2001). Expulsion from Burrum Coal Measures source units should have been even less complete. Again, sources nearer the basin margins were probably less mature by the Santonian. Although gas is the most likely hydrocarbon phase to have been expelled at this time, late generated Cretaceous-sourced oil can not be totally ruled out in the Maryborough Basin.

### Key Unknowns

Knowledge of the offshore Maryborough Basin is limited to geophysical data, with the stratigraphy of the Mesozoic sequences extrapolated from onshore wells and outcrop. The geology of the offshore Cainozoic sequence, which is up to 1500 m thick, is largely unknown except from stratigraphic drilling at the northern end of Fraser Island. The eastern limits of the Maryborough Basin are also poorly constrained – the shelf break is used as an approximation in this report, but Maryborough Basin sediments might also be present on the continental slope.

The amount of Maryborough Basin sediments removed during the two main erosion events is poorly constrained. Hill (1994) concluded that up to several kilometres of section were removed in the Late Cretaceous. The amount of material removed during the earlier Late Jurassic erosional event is unknown.

Poor reservoir characteristics are a major risk factor for potential Maryborough Basin reservoirs. Lipski (2001) regarded the identification and prediction of areas that exhibit favourable reservoir facies or porosity enhancement as a key unknown.

### Environmental Sensitivities

Hervey Bay is a Marine Park, and the north of the Maryborough Basin offshore lies within the Great Barrier Reef Marine Park, in which petroleum exploration activities are prohibited. The offshore Maryborough Basin also underlies whale migration paths between May and October. The onshore Maryborough Basin is extensively settled, including residential, farming and tourist areas. Fraser Island is both a World Heritage Area and a National Park.

### Conclusions

The Maryborough Basin is considered to have good potential for gas, sourced from and sealed within the Cretaceous Maryborough Formation. Charge and post-inversion seal are low risk, but reservoir quality is problematical, so explorers would need to seek reservoir sweet spots. Oil is also possible within the Cretaceous section, but less likely due to the timing of trap formation versus oil generation.

Reservoirs within the Late Triassic Myrtle Creek Sandstone are likely to be very deep and tight in the central basin, whilst trap breach of any such reservoirs near the basin margin is probable. A key event in basin history is Santonian inversion, which probably breached many older traps, whilst creating new ones in the form of northwest-trending anticlines and fault-bound rollovers. The offshore Cainozoic section is virtually unknown. It could conceivably contain sealed hydrocarbon reservoirs, sourced from the Cretaceous section.

Environmental concerns are likely to severely limit petroleum exploration within the offshore Maryborough Basin. The likelihood of gas rather than oil, and tight reservoirs, will add further economic disincentives to offshore petroleum exploration. Onshore however, the Maryborough Basin has had one significant gas show from only four exploration wells drilled, and may prove to be a viable gas province.

## *Proposed Future Investigations*

It is apparent that the geology of many areas of the central eastern Australian margin is very poorly known. As stated earlier in this report, basement rocks covered by a veneer of Cainozoic sediments underlie a large part of the offshore east coastal region (Figure 1). Of the sedimentary basins known to occur offshore, only the Sydney Basin is relatively well known, and then only from geophysical data as no well has been drilled offshore. Parts of the Maryborough Basin are known from a BMR *Rig Seismic* survey (Hill, 1994), but further south, the offshore Nambour Basin is virtually unknown, as is any possible extension of the underlying Ipswich Basin. Off the New South Wales north coast, the Yamba Trough of the Clarence-Moreton Basin is known from limited seismic, gravity and magnetic data (Wells and O'Brien, 1994), but even sparser seismic data suggest a more extensive sedimentary section of unknown age or affiliation in this area (Alder, 2001). Further south, it is not yet known whether or not the small onshore Lorne Basin extends offshore.

In addition to these basins, small graben and half-graben associated with Tasman Sea rifting may occur within basement dominated shelf and slope areas. One such feature is known to exist on the continental slope near Bateman's Bay (Colwell and others, 1993), and similar graben are known from the northern end of the Tasman Sea rift (Stephenson and Hill, 2002); these features may be more widespread along the central eastern margin than is currently known.

To address these and other unknowns off this margin, Geoscience Australia proposes to undertake a research cruise in the area at some future date. We intend to acquire swath, shallow seismic, gravity and magnetics data, and take dredge and gravity core samples. Data acquisition will be targeted on the upper continental slope, plus those areas of the continental shelf identified above as requiring further investigation.

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# Appendix 1 – Sydney Basin Detailed Stratigraphy.

*This Appendix is largely based upon Chapter 3 of Maung and others, 1997.*

## 1 INTRODUCTION

The stratigraphy of the onshore Sydney Basin has been described, amongst others, by Mayne and others, (1974), Branagan and others, (1979), Passmore (1979), Herbert (1980), Scheiber (1993) and Veevers and Powell (1994). The stratigraphy adopted by Santos (1993; Grybowski, 1992) in NSW P/10 has been followed, but modified to take into account the AGSO Time Scale Compilation of 1996. It also takes account of radiometric dates based on SHRIMP zircon dating (Roberts and others, 1996) and stratigraphic correlations in the southern Sydney Basin (Tye and others, 1996). The resulting stratigraphy is shown in Figure 7 and a schematic cross section, based on Herbert (1980) is shown in Figure 8.

## 2 REGIONAL STRATIGRAPHY

### 2.1 Basement

#### Lachlan Fold Belt

The Lachlan Fold Belt is the stable craton exposed to the south and west of the Sydney Basin, comprising Ordovician to Devonian sediments and Carboniferous felsic volcanics. Sydney Basin sediments unconformably overlie and onlap Lachlan Fold Belt sequences and by simple projection of the regional strike trends, most of the onshore Sydney Basin overlies rocks of the Lachlan Fold Belt. Supporting evidence for this comes from the composition of quartzose-feldspathic sandstone xenoliths retrieved from a diatreme at Mogo Hill south of Gosford which compositionally are very similar to Silurian and Devonian rocks of the eastern Lachlan Fold Belt (Emerson and Wass, 1980; Veevers and Powell 1994). Regionally the Lachlan Fold Belt coincides with economic basement for much of the Sydney Basin.

#### New England Fold Belt

The southern New England Fold Belt comprises sequences deposited due to Carboniferous subduction related processes, incorporating a subduction complex, fore-arc basin, and dacitic to andesitic volcanic arc. These sequences include intertonguing marine and non-marine successions with numerous laterally extrusive felsic volcanic eruptives occurring in units such as the Mt Johnstone Conglomerates, Paterson Volcanics and Seaham Formation. Sydney Basin sediments unconformably overlie the Seaham Formation, a continental glacigene sequence of Late Carboniferous age containing tillites, varve shales, tuffs, lithic sandstone and conglomerates. The Seaham Formation coincides with economic basement in the northern onshore Sydney Basin. The hiatus separating these sediments from the overlying Sydney Basin sequence is >15 Ma (Roberts and others, 1995) and presumably represents the time during which the subduction zone shifted eastwards.

The present boundary between the Sydney Basin and the New England Fold Belt is in part structural, and coincident with the Hunter Thrust. As the major north-south compression which produced this did not occur until well into the Early Permian, initial deposition of Early Permian sediments was contiguous across the fold belt (Veevers, 1984); evidence for this includes outliers in the Cranky Corner Basin, and truncation observed in the offshore (Figure 35). Consequentially the Early Permian depositional and structural relationships along the northern margin are uncertain, having been obliterated following thrusting and uplift.

Based on similarities of seismic character and magnetic anomaly response, equivalents of the Upper Carboniferous are anticipated to constitute or underlie economic basement eastwards where the New England Fold Belt extends beyond the coastline, and southwards beneath the Offshore Uplift. Absolute age dating and correlations with more easterly terranes of the New England Fold Belt (Stroud-Gloucester and Myall Synclines) indicate that erosion, and the corresponding hiatus between the basal Sydney Basin and underlying Carboniferous, may increase in that direction. Across structural culminations in the offshore Permian sediments may unconformably overlie equivalents of the Namurian (about 320 Ma) Johnsons Creek Conglomerate.

## 2.2 Early Permian - Lower Dalwood Group and Talaterang Group

A complex Upper Carboniferous basement, including volcanics and fluvio-glacial valley-fill conglomerates, is unconformably overlain in the northern and central onshore Sydney Basin by the Lower Permian Dalwood Group. The Dalwood Group crops out in the northwest of the Hunter Valley and across the Lochinvar Anticline. The Group is divided into the Lochinvar, Allandale, Rutherford and Farley formations. The following descriptions of these units are largely from Hawley and Brunton (1995). Stage ages in Ma for particular formations are according to the AGSO Permian biozonation and stratigraphy chart of Nicoll and others (1998).

The **Lochinvar Formation** is the basal unit of the Dalwood Group. It consists of poorly fossiliferous siltstone, claystone, sandstone and interbedded basalt flows, pyroclastics and tuff. Crinodal limestone has also been recorded near the base. The formation was deposited in a shallow marine environment, the upper part being glacigenic (Veevers and Powell 1994). The Lochinvar Formation has a thickness of 835 m in the Lochinvar area. Roberts and others (1995) dated it as Sakmarian (293-285 Ma); Nicoll and others (1998) assigned it to the late Asselian and early Sakmarian, at 295-290 Ma).

The **Allandale Formation** overlies, and is regarded as a local facies variant of the Lochinvar Formation. The Allandale Formation consists of lithic sandstone and conglomerate containing abundant invertebrate fossils indicating that it was deposited in a sub-littoral to shallow marine environment. It is 150 m thick in its type section and was dated as late Sakmarian (290-286 Ma) by Nicoll and others (1998).

Together the Lochinvar and Allandale formations are referred to as the Lower Dalwood Group and in places where they comprise chiefly pyroclastics, tuffs and acid volcanics they are considered to constitute economic basement. The combined maximum penetrated thickness of the Lower Dalwood Group is 1090 m at East Maitland-1, although in the offshore substantially greater thicknesses are indicated. It has been suggested that portions of the Lower Dalwood Group were deposited within a largely northwest-southeast trending depression, with elevated ground to the southwest and a northwest-southeast trending high of Carboniferous rocks to the north (McClung, 1980). Evans and Migliucci (1991) regard elevations of the high and coarsening-upward facies as evidence of the first compressive pulse of the New England and Currarong orogens. Although entirely speculative, such a mechanism is more harmonious with later development of the Sydney Basin than the interpretation that the Lower Dalwood Group represents deposition during a volcanic rift phase, as proposed by Veevers and Powell (1994).

In the southern Sydney Basin the comparative units to the Lower Dalwood Group, the Talaterang Group, contain a lesser proportion of volcaniclastic and correspondingly greater abundance of siliciclastic sediments derived from the adjacent Lachlan Fold Belt. Sporadic occurrences of basalt are interpreted as reflecting a prevailing extensional rift regime associated with the inception of the Sydney Basin, prior to its transformation into a foreland setting. This initial phase of extension is correlated with the deposition of the Clyde Coal Measures, Pigeon House Creek Siltstone and Wasp Head Formation (Tye and others, 1995) which together constitute the redefined Talaterang Group.

The **Clyde Coal Measures** unconformably overlie Ordovician metasedimentary basement and are disconformably overlain by the Yadboro Conglomerate, or where that is absent, the Snapper Point Formation. It comprises a low energy alluvial system consisting of interbedded fine-grained sandstone, carbonaceous siltstone and discrete coal seams up to 1 m thick. Sandstones dominate towards the top of the section, which at its type locality is approximately 45 m thick. It is only locally developed in the southern onshore Sydney Basin.

The **Pigeon House Creek Siltstone** is interpreted as a mud-rich alluvial deposit containing channel sands and finer grained carbonaceous siltstones, representing overbank deposits. The sequence unconformably overlies Ordovician strata and is disconformably overlain by the Yadboro Conglomerate. In its type section it is approximately 45 m thick. Both the Pigeon House Creek Siltstone and the Clyde Coal Measures are interpreted to be Early Permian in age, probably Sakmarian to Artinskian.

The **Wasp Head Formation** is only known from a small stretch of coastline near Bateman's Bay. Here the formation unconformably overlies the folded deep-marine shales of the Ordovician Wagonga Beds and is in turn overlain by the Pebbley Beach Formation. The type section is dominated by fine to medium grained sandstone and breccia units towards the base. These are poorly sorted, internally chaotic and surrounded by a silt rich matrix. They are also eastward thinning, suggesting palaeo-flow to the east, whereas crossbedding suggests northward flowing palaeo-currents, probably shoreward-prograding upper shoreface facies (Tye and others, 1995). Based on bivalve and brachiopod faunas the Wasp Head Formation is considered Sakmarian in age. Nicoll and others (1998) assigned it to the interval 290-286 Ma.

Both the Clyde Coal Measures and the Reids Dome Beds were deposited into developing grabens that contain localised mud-rich alluvial and lacustrine successions. There seems to have been a northward sediment dispersal phase that predated thrust loading from the east and a change in provenance. It was because of this change in provenance that Tye and others (1995) distinguished the Talaterang Group from the overlying Shoalhaven Group. This change is taken to coincide with the cessation of rifting and the onset of foreland loading development in the Sydney Basin.

### 2.3 Early Permian - Upper Dalwood Group, Greta Coal Measures, and Lower Shoalhaven Group

Together the Rutherford and Farley formations are referred to as the **Upper Dalwood Group**. Herbert (*in* Branagan and others, 1979) considered most of the Upper Dalwood Group to be a regressive sequence that culminated with the delta plain and swamp environment deposition of the Greta Coal Measures. The Upper Dalwood Group and Greta Coal Measures in the northern Sydney Basin are at least 1500 m thick onshore. Seismic evidence supports their extension to the offshore across the Newcastle Syncline.

The **Rutherford Formation** consists of siltstone and minor sandstone with thin limestone and marl horizons occurring in the Pokolbin area of the Hunter Valley. The Rutherford Formation was deposited in a shallow marine environment and in its type section it is 385 m thick. Based on interpreted seismic sections, much thicker sequences could be present in the offshore, within the eastern segment of the Newcastle Syncline and Offshore Syncline. The Rutherford Formation is dated as latest Sakmarian to Artinskian (286-275 Ma) by Nicoll and others (1998).

The **Farley Formation** overlies, and is in part contemporaneous with, the Rutherford Formation. It consists of fossiliferous silty sandstone that becomes coarser towards the source area in the north. It was deposited in a pro-delta environment and is dated as latest Artinskian (275-274 Ma) by Nicoll and others (1998). At its type section it is 300 m thick. Sands within the Farley Formation constitute a potential reservoir target, as evidenced by interpreted untested gas sands in the Jerrys Plains-1 well. The upper Dalwood Group units represent deposition during a period of marine transgression. Collectively they attain a thickness of 600 m towards the northern margin of the Basin, whereas in the equivalent section through Sydney they attain a thickness of more than 480 m (Lohe and others, 1992).

The **Greta Coal Measures** are distributed along the northern edge of the Sydney Basin as a wedge of coal bearing deltaic sediments, following an influx of detritus shed from the emerging New England Fold Belt to the north and northeast. Across the Muswellbrook Anticline they overlie Early Permian Dalwood Group sediments and across the Lochinvar Anticline they overlie the marine Farley Formation. In their type area they are 63 m thick but attain a thickness of up to 480 m along the northern margin (Lohe and others, 1992). They comprise sandstones, conglomerates, coals (including individual seams of up to 8 m thick), siltstones and claystones. The unit was deposited as a deltaic, fluviatile sequence and is dated as Early Permian but with substantial diachroneity. Roberts and others (1995) showed it to be substantial younger across the Muswellbrook Anticline (278 - 269 Ma) than across the Lochinvar Anticline (278-275

Ma), age trends which indicate both a westerly younger and disconformable base for the unit. Based on Roberts and others (1996) age dating, the Greta Coal Measures are in part time-equivalent to the overlying Branxton Formation. This may well be the case, but Nicoll and others (1998) assigned a much narrower age range to the Greta Coal Measures of 274-273 Ma (earliest Kungurian).

Strong discontinuous reflectors observed on seismic sections immediately offshore from the northern Sydney Basin are correlated with the Greta Coal Measures section and slight angularity can be observed with underlying reflectors (Maung and others, 1997). The sequence thickens marginally into the Newcastle Syncline and eastwards across the flank of the Offshore Uplift (Figures 36, 37). The Greta Coal Measures and their Lower Permian offshore equivalents represent one of the primary source rock units in the Offshore Sydney Basin (Maung and others, 1997).

Disconformably and erosionally overlying the Talaterang Group in the southern Sydney Basin is the **Shoalhaven Group.** It comprises marine shelf to coastal plain sediments in the east and coarse clastic, high-energy alluvial (glacigene) facies of the Yadboro and Tallong Conglomerates in the west. The group is essentially a marine transgressive unit that passes westwards into a fluvial facies towards the basin margin and overlaps the underlying fluvioglacial Talaterang Group. High-energy braided floodplains developed with sediment dispersal to the east.

The **Tallong Conglomerate** infills channels incised into basement. These channels, which are up to 3 km wide and 300-400 metres deep, can be traced from the Lachlan Fold Belt eastwards approximately 100 km to the present coastline near Nowra (Herbert 1980). The **Yadboro Conglomerate** occurs in a smaller, but similar easterly trending channel, which can be traced some 25 km inland from the coastline near Ulladulla. Both units represent deposition within the tributaries of the fluvioglacial drainage pattern. Tye and others (1995) interpreted these as lateral equivalents to the Pebbley Beach and Snapper Point formations. In several wells coals have been reported above the Tallong Conglomerate within a very fine-grained sandstone and carbonaceous shale unit. Although thin (<10 m) it has been suggested that they constitute a separate, non-marine coal measure sequence, the **Yarrunga Coal Measures** (Tye and others, 1995). These may be equivalent to the Greta Coal Measures of the northern Sydney Basin.

The **Pebbley Beach Formation** unconformably overlies the Wasp Head Formation. It is dominated by siltstone, with minor sandstone, conglomerate and coal. Channelling and crossbedding are evident; the formation most probably was deposited in a coastal environment, becoming a low energy tidal flat towards the top. Diamictites and large dropstones suggest the presence of ice rafting during deposition.

Veevers and Powell (1994) include Pebbley Beach Formation deposition as part of the initial marine transgression of the basin. The western boundary of this transgression reached the Lapstone Monocline, interpreted to be the western wall of an extensional or rift depression. This structural boundary was not over-stepped until transgressed by the marine Snapper Point Formation, this more westerly transgression being interpreted by Veevers and Powell (1994) as reflecting a fundamental change in the Sydney Basin's burial history from active extension to thermal sag. By the end of Snapper Point deposition marine transgressions had drowned all the previous terrestrial environments in the southern Sydney Basin. In the northern Sydney Basin the corresponding event is the transgression of the Maitland Group over the Greta Coal Measures (Veevers and Powell; 1994).

The **Snapper Point Formation** is a broadly distributed sequence, which interfingers with and overlies, the Tallong and Yadboro Conglomerates, or unconformably overlies basement if those units are not present. It is a succession of medium grained sandstones interbedded with siltstone and wave-rippled conglomerates. The formation was deposited in a shallow marine environment, probably on a storm-dominated shelf. In the west, minor fluvial intervals present towards the top of the unit are interpreted as reflecting deposition of local braided stream regressive sequences during minor sea level fluctuations, superimposed on an overall large-scale transgression. The Snapper Point Formation has a greater portion of sandstone than the rest of the subgroup and as such constitutes an important reservoir target, as highlighted by the presence of untested, possible gas bearing, sands in the Dural South-1 well (Maung and others, 1997). The Snapper Point Formation is dated as earliest Kungurian (274-273 Ma) by Nicoll and others (1998), and is at least partly correlated with the Greta Coal Measures.

### 2.4 Early to Late Permian - Branxton Formation, Wandrawandian Siltstone, and Muree/Nowra Sandstones.

According to Evans and Migliucci (1991) these constitute a new cycle of foreland deposition above the Lower Coal Measures and their equivalents. Alternatively the Maitland Group may have been deposited during the waning stage of the Early Permian to early Late Permian transgression (Maung and others, 1997). The Maitland Group is subdivided into a lower fine-grained marine section and an upper fine-grained marine section separated by minor regressive sandstone (Muree/Nowra Sandstone). The lower marine section is called the Wandrawandian Siltstone in the south and the Branxton Formation in the north. The upper marine section is referred to as the Berry Siltstone in the south and the Mulbring Siltstone in the north. The regressive sandstone sequence is referred to as the Nowra Sandstone in the south and the Muree Sandstone in the north. The sandstone sequence represents a basin wide potential reservoir target.

The **Branxton Formation** consists of sandstone, siltstone, conglomerates, coals and rare tuffs. It is more conglomeratic towards the base, with silty sandstone and siltstone becoming common upwards. It is largely a shelfal facies, but the presence of coal and carbonaceous matter indicates a proximity to peat swamps and coastal environments (Evans and Migliucci, 1991). In the middle of the formation is a 30-60 m thick richly fossiliferous siltstone and claystone unit, the “Fenestella Shale”. In the Lochinvar and Belford Dome areas the unit is sub-divided into the lower Elderslie Formation, Fenestella Shale, Belford Formation, and Muree Sandstone. The thickest Branxton Formation interval of approximately 900 m occurs along the northern margin of the Basin (Lohe and others, 1992). SHRIMP dating of contained tuffs indicates a Kungarian (272 Ma) age (Maung and others, 1997). Nicoll and others (1998) agreed with this, and dated both the Branxton Formation and the Wandrawandian Siltstone at 273-267 Ma.

The **Wandrawandian Siltstone** is up to 200 m thick and rapidly succeeded, but did not overstep, the Snapper Point Formation in the south, extending westwards to the hinge-line coincident with the Lapstone Monocline (Evans and Migliucci, 1991). It was deposited in a wave-base environment. Veevers and Powell (1994) noted that it included at the top of the sequence the first occurrence of tephra, taken to indicate the onset of a period of mid-Permian volcanism. However, Roberts and others (1995) noted that tuffs occurring in the Greta Coal Measures and Branxton Formation are older, and coincide with late stages of igneous activity in the Myall region to the north.

The **Muree Sandstone** overlies the Branxton Formation and consists of sandstone with minor conglomerate and siltstone. The Muree Sandstone is up to 180 m thick in the northeastern basin, but thins to the west. It reaches a maximum thickness of 90 m in the southern and central basin. At its type section it is 82 m thick and in East Maitland-1 it had a penetrated thickness of 108 m. The unit is dated as Roadian to early Wordian (267-265 Ma) by Nicoll and others (1998), and was deposited in a littoral environment.

The **Nowra Sandstone** was deposited in a middle/upper shoreface to foreshore environment under the influence of storm-generated waves and north to northeasterly directed longshore currents (Le Roux and Jones, 1994) during a regressive-transgressive episode. The lower Nowra Sandstone was deposited during major regression forming a downlap sequence that becomes progressively younger eastwards as it passes laterally into the Wandrawandian Siltstone. During subsequent transgression the shoreline shifted position by more than 50 km (Le Roux and Jones, 1994) the upper Nowra Sandstone representing successive sediment wedges that backstepped onto the basin margin as the sea level rose. This rise in sea level also caused a transition, both laterally eastward and vertically, from the Nowra Sandstone into the mid-shelf deposits of the Berry Siltstone (Le Roux and Jones, 1994). The upper surface of the Nowra Sandstone is therefore diachronous and becomes progressively younger westwards as transgression ensured. The Nowra Sandstone now forms prominent cliffs around the Shoalhaven River area. Nicoll and others (1998) date it at the same age as the Muree Sandstone. The Nowra and Muree Sandstones are considered primary reservoir targets in the offshore areas (Maung and others, 1997).

### 2.5 Middle to Late Permian - Mulbring Formation and Berry Siltstone

The **Mulbring Formation** of the northern Sydney Basin is a succession of grey siltstone and minor claystone that conformably overlie either the Muree Formation or the Branxton Formation. It is 330 m thick in its type section and 393 m thick in Planet East-1 well (Hawley and Brunton, 1995). On the southern flank of the Lochinvar Anticline Narrabeen Group sediments unconformably overlie it. In the western part of the basin, Glen and Beckett (1993) interpreted the siltstone as a marine to prodelta succession passing laterally into and overlain by delta front sandstones, siltstones and minor coals of the Wittingham Coal Measures and Saltwater Creek Formation. For this reason Evans and Migliucci (1991) interpret the top of a depositional cycle as coincident with the top of the Wittingham Coal Measures. Again the basal boundary of the Mulbring Siltstone is likely to be diachronous. The unit was dated as 264-262 Ma by Roberts and others (1996), but Nicoll and others (1998) assigned it an age of around 265-263.5 Ma, placing the formation within the Wordian to earliest Capitanian stages.

According to Evans and Migliucci (1991), the Mulbring Formation was deposited during periods of a widespread basin deepening in which deposition occurred below the wave base. In their scheme the onset of Mulbring Formation deposition is interpreted to coincide with the commencement of another foreland depositional cycle that culminated in shallow marine and shoreface facies of the Saltwater Creek Formation and delta plain facies of the Wittingham Coal Measures and equivalents.

The **Berry Siltstone** is equivalent in the southern onshore Sydney Basin to the Mulbring Formation (Figure 7). It too was deposited during basin deepening, in a mid-shelf environment. The top of this transgression, corresponding to a maximum flooding surface, occurs within the Berry Siltstone according to Herbert (1995). The Berry Siltstone has a maximum thickness of approximately 550 m in Stockyard Mountain-1. It consists predominantly of siltstone composed of illite, quartz, volcanic and non-volcanic lithic fragments (Bowman, 1973). The Berry Sandstone is dated as late Wordian (265-264 Ma) by Nicoll and others (1998). Just as shallower marine and terrestrial facies succeed the Mulbring Formation, so too the Broughton Sandstone and Pheasants Nest Formation at the base of the Illawarra Coal Measures succeed the Berry Siltstone. These are deltaic and fluvial sequences derived from the craton to the west, although the Broughton Sandstone also contains volcaniclastic detritus associated with the Gerringong Volcanics (Maung and others, 1997).

The **Budgong Sandstone** reaches a maximum thickness of 370 m in the southern Sydney Basin, just west of Kiama. The sandstone is fine grained and similar in composition to the Berry Siltstone but deposited in a littoral environment. Towards the top of the sequence grain size and sorting increase. This reflects the lower Budgong having been deposited below the wave-base whereas the upper Budgong was deposited above the wave-base (Bowman, 1973). It is dated as earliest Capitanian (264-263 Ma) by Nicoll and others (1998). Latite flows are interbedded towards the top of the unit attesting to increasing local volcanism. The relatively large amount of sand-size detritus appears to originate from an immature source area, the sands being predominantly volcanic rock fragments and plagioclase. This immaturity may reflect the re-emergence of the Offshore Uplift as a provenance at about this time.

### 2.6 Gerringong Volcanics

The Gerringong Volcanics is a collective term applied to five latite flows interbedded within the Budgong Sandstone and two flows within the overlying Pheasants Nest Formation (Bowman, 1973). They attain a maximum thickness of approximately 440m (Packham, 1969). Tye and others (1996) saw their occurrence as marking the onset of a major phase of shoshonitic volcanism and associated reorganisation of sediment provenance, interpreted by Maung and others (1997) as heralding a discrete new phase of flexural loading and increased compression.

Interpretation of aeromagnetic and marine magnetic data indicate that the onshore distribution of the Gerringong Volcanics can be extended to the offshore, coincident with an area characterised by short-wavelength high amplitude anomalies. This appears to be confined to the southern offshore Sydney Basin, across the Offshore Uplift (Grybowski, 1992). The Gerrigong Volcanics probably also coincide with high amplitude reflections observed on the seismic lines traversing this area at depths of about 0.6 seconds TWT (Maung and others, 1997). Veevers and Powell (1994) dated the oldest Gerringong Volcanics at 258 +/- 5 Ma, most probably placing them within the early Wuchiapingian stage of the Late Permian according to the Geoscience Australia timescale. They also equated the Gerringong Volcanics to sporadic occurrences of magmatism elsewhere in the region including the Milton Monzonite, Bawley Gabbro and Microgranite, and gabbro now located on the dispersed Dampier Ridge.

## 2.7. Late Permian Coal Measures

The Illawarra Coal Measures of the southern onshore Sydney Basin and the Tomago and Newcastle Coal Measures of the northern onshore Sydney Basin, together with their westerly equivalents, comprise a Late Permian coal measure interval that extends almost across the entire onshore basin. In the offshore, equivalents of the Tomago and Newcastle Coal Measures can be interpreted with certainty within the narrow coastal corridor of the Offshore Syncline. However eastwards they are tightly up-turned and truncated as a result of erosion following post-depositional thrusting and compression by the Offshore Uplift. As such they are considered to have limited sourcing potential in the offshore area (Maung and others, 1997).

Late Permian coal measure deposition in the onshore northern Sydney Basin occurred in three major regressive phases: the Lower Tomago, Upper Tomago and Newcastle Coal Measures. Separating these were intervening marine transgressions of the Kulnura Marine Tongue and Dempsey/Denman Formations and their respective correlatives. These units represent both regionally significant potential source rock and reservoir units within close proximity.

The **Tomago Coal Measures** are divided into three formations: the Wallis Creek, Four Mile Creek and Dempsey Formations. The Wallis Creek Formation comprises over 300 m of sandstone, siltstone, claystone and thin coals. The Four Mile Creek Formation is the principal coal bearing unit consisting of coal, siltstone, claystone and sandstone. Although only 77 m thick at its type section, it is known to exceed 450 m thickness in the Williamtown area close to the coastline, where the total Tomago Coal Measure thickness may exceed 1250 m. The Dempsey Formation reaches a thickness of at least 590 m, and consists of siltstone, claystone, sandstone and minor coal (Hawley and Brunton, 1995).

At the top of the Wallis Creek Formation the **Kulnura Marine Tongue** was deposited during a marine incursion. It is a bioturbated siltstone and sandstone unit about 160 m thick, and is recognised in the southern parts of the Hunter Coal Field. Herbert (1984) described the Kulnura Marine Tongue as an essentially dark-grey to black bioturbated, fossiliferous, marine siltstone. Sandy and conglomeratic facies occur towards the top and towards the basin margins. In the south these coarser grained facies are known as the **Erins Vale Formation**, and in the north as the **Bulga Formation**. The thickest development of the combined Kulnura Marine Tongue and Erins Vale Formation appears to be in the Balmain Bore where it is over 200 m thick. The total unit thins towards the western margin and is erosively overlapped by the Marrangaroo Conglomerate. A distinctive conglomeratic facies within the Erins Vale Formation occurs over a well-defined area in the central portion of the basin, where the conglomerate is interbedded with fine-grained marine sediments. The conglomerate is apparently contemporaneous with the widely distributed **Marrangaroo Conglomerate**, a fluvial pebbly sandstone to cobble conglomerate extending from the western margins of the basin towards the east. A conglomeratic alluvial plain prograded eastwards into the sea, resulting in near-shore and delta front sequences of interbedded conglomerates, coarse sandstones and siltstones. Numerous hydrocarbon shows have been recorded in both the Erins Vale Formation and the Marrangaroo Conglomerate (Herbert, 1984).

The Tomago Coal Measures thin onto the Lochinvar Anticline, and across the culmination are completely absent due to a contribution of non-deposition, depositional thinning and subsequent erosion. The Wittingham Coal Measures, which occur to the west of the Lochinvar Anticline are equivalents of the Tomago Coal Measures. Roberts and others (1996) dated the Tomago Coal Measures between 262 - 252 Ma (the Late Permian Capitanian to Changhsingian Stages of Nicoll and others, 1998). Equivalents of the Tomago Coal Measures (and overlying Newcastle Coal Measures) can be observed on seismic data east of the coastline. An irregular, laterally incoherent, high amplitude reflection package located immediately below the Post-Breakup Unconformity can be traced across the Offshore Syncline (Maung and others, 1997). Uplift and erosion to the north has truncated its original distribution (Figure 36). These sediments appear to be confined to the Offshore Syncline and the Newcastle Syncline, where they are anticipated to provide a regional source sequence (Maung and others, 1997).

The **Newcastle Coal Measures,** occurring across the onshore northern Sydney Basin, have been extensively described. Divided into numerous sub-groups, formations and members, Hawley and Brunton (1995) identified and described a total of 59 separate stratigraphic constituent units of this coal measures sequence. Individual units consist of varying proportions of greywacke, siltstone, mudstone, lithic sandstone and coal. The basal unit is the Waratah Sandstone, a medium grained sandstone, particularly well sorted in the middle and 20 m thick in its type section. This sandstone is a potential reservoir target. Nicoll and others (1997) dated the Newcastle Coal Measures as 256.5-252.5 Ma (late Wuchiapingian to Changhsingian Stages). The Late Permian Coal Measures are up to 1200 m thick onshore and probably attained a greater thickness in the offshore Newcastle Syncline and across the eastern flank of the Offshore Uplift, prior to subsequent uplift and truncation (Maung and others, 1997).

The **Illawarra Coal Measures** are the southern onshore Sydney Basin equivalents of the Newcastle Coal Measures, and range in age from 263-253 Ma (Capitanian to Changhsingian Stages; Nicoll and others, 1998). They consist of sandstone, siltstone, shale and coal seams, with minor conglomeratic and tuffaceous beds. In the Southern Coalfields they have an average thickness of 210 m, thickening to the north (> 500 m), and thinning to less than 50 m in the south and west; individual coal seams may be several metres thick (Lohe and others, 1992). Contemporaneous volcanic activity is evidenced by tuffaceous sections within the seams. The **Pheasants Nest Formation** is the basal formation of the coal measures. It was deposited in a delta plain environment, sediments grading from coarse sandstone at the base to siltstone and coal at the top. Delta plain deposition was succeeded by a marine transgression during which up to 37 m of sandstone was deposited: the Erins Vale Formation. It is an interdistributary bay facies equivalent of the Kulnura Marine Tongue found in the northern offshore portion of the Sydney Basin.

There is a marked erosional event at the top of the Erins Vale Formation that is disconformably overlain by a series of upward fining cycles commencing with the Wilton Formation. Deposition of these cycles was predominantly fluvial, occurring on a distributive delta floodplain (Bowman, 1973). The top of the Illawarra Coal Measures is placed at the top of the highest coal.

By analogy with the Tomago and Newcastle Coal Measures, the Illawarra Coal Measures are anticipated to extend into the offshore, and like their northern Sydney Basin counterparts are now most probably confined to the adjacent Offshore Syncline, following subsequent uplift and erosion (Maung and others, 1997).

## 2.8 Triassic

Triassic deposition in the Sydney Basin is sub-divided into three units, each having distinctly different gross lithological characteristics (Herbert, 1980). The oldest unit is the Narrabeen Group, which ranges in age from Early to Middle Triassic. The Group comprises up to 800 m of lithic conglomerate, quartz-lithic sandstone, and red, green, and grey shale, and is in-turn subdivided into Lower, Middle and Upper Narrabeen on the basis of depositional episodes. The overlying Hawkesbury Sandstone is up to 290 m thick and is of Middle Triassic age. The youngest unit, the Wianamatta Group, is also of Middle Triassic age and up to 300 m thick. It is mainly shaly with sporadic thin lithic sandstones.

The **Narrambeen Group** was assigned a Late Permian to Middle Triassic age by Packham (1969), but Nicoll and others (1998) date the base of the Group at 250 Ma, within the Early Triassic. It crops out extensively on the southern side of the Hunter Valley, and unconformably overlies the Newcastle Coal Measures or older units across structural highs, such as the Lochinvar Anticline where it unconformably overlies sediments of the Maitland Group. The maximum known thickness of the Narrabeen Group is 808 m, penetrated in the Longley-1 well, and the section comprises fluvial, paludal and lacustrine facies. The Narrabeen Group forms a non-commercial gas reservoir onshore, but is of limited areal extent offshore (Maung and others, 1997).

Uplift of the Lachlan Fold Belt to the southwest of the Sydney Basin tilted and led to the erosion of Late Permian and Early to Middle Triassic sediments in the southern Sydney Basin (Herbert, 1980). This uplift initiated the onset of coarse, quartzose, **Hawkesbury Sandstone** deposition. This sand was probably derived from Upper Devonian quartzites of the Lachlan Fold Belt. Uplift in the southwest may have reflected increased thrust loading to the northeast, with the resulting change in palaeocurrent direction transporting sediments in a northeasterly direction. Encroachment of the Hawkesbury Sandstone to the northeast was time transgressive, so that deposition of the Upper Narrabeen Group in the northern Sydney Basin is coeval with Hawkesbury Sandstone deposition in the south. Fine grained floodplain deposits are rare within the Hawkesbury Sandstone, but floodplain sediments of the Mittagong Formation cap it; these attain a thickness of only 6-15 m.

The **Wianamatta Group** was deposited during a period of major regression. Sediments were deposited in an unbroken sequence, environments grading upwards from subaqueous, to shoreline, and alluvial (Herbert, 1980). Extensive floodplains with channels, levees, and backswamps (**Bringelly Shale**), were formed behind a sandy barrier island complex (**Minchinbury Sandstone**), which prograded across a shallow marine or estuarine laminated silt sequence (**Ashfield Shale**).

No Late Triassic, Jurassic or Cretaceous sedimentation is preserved within the Sydney Basin. However, indirect evidence for Jurassic sedimentation comes from remnants that have been preserved where they collapsed into Jurassic volcanic breccia pipes, and Late Mesozoic sediments retrieved in offshore grab samples (AGSO, 1993). Large proportions of those associated with the breccia pipes consist of a black carbonaceous siltstone matrix containing well preserved Early Jurassic spore assemblages.

### 2.9 Post-Breakup Section

The continental shelf east of Newcastle contains an uppermost wedge of Cainozoic age. This wedge is up to 500-700 m thick and composed of two units, an upper shallow water carbonate unit and a lower prograding clastic delta. Projected ages of these units span the interval from mid-Oligocene to Quaternary and represent a partitioning of the shelf both in time (at the middle Miocene) and space (at the outer shelf plain) between clastics and carbonates. A relatively detailed account of the age and composition of shallow core and grab samples collected offshore Sydney Basin in relatively recent times is given in AGSO (1993).

## 3 SEISMIC STRATIGRAPHY

Maung and others (1997) made ties to the offshore using shallow reflection data coverage across the immediate coastal zone (Boyd, 1996) and ties to offshore engineering holes. In the absence of any offshore petroleum wells interpretation of the offshore seismic stratigraphy remains conjectural. Indirect ties have been made by “jump correlation” from adjacent onshore seismic coverage to nearby shallow marine data. Grybowski (1992) described how the western end of offshore line 81-24 was tied to Dural South-1 via a single fold seismic survey line acquired by Australian Oil and Gas (Short, 1963). Dural South-1 was drilled in 1966 and intersected 828 m of Triassic and 2217 m of Permian section and 10 m of tuff of undetermined but probable Early Permian age, lying below the Pebbley Beach Formation. Terminating at a total depth of 3059 m it is the deepest well in the Sydney Basin. Unfortunately correlation between Dural South-1, located 26 km from the coastline, and the western end of Line 81-24, located 7 km offshore, is made all the more tenuous because correlation of events along the intervening seismic grid includes 1960’s vintage data which is of poor quality (Maung and others, 1997).

The geology penetrated during shallow engineering borehole drilling, to depths of approximately 150 m below sealevel off the Sydney coastline along several east-west transects, provides some limited shallow geological control in the area immediately offshore Sydney Harbour. The penetrated geology, tied to sparker and magnetic data, showed a westerly dipping sequence of Narrabeen Group sediments below the Hawkesbury Sandstone extending out to the Bulgo Sandstone and Stanwell Park

Claystone. Westerly dips of approximately 4° -5° were encountered in the east, reducing to 2°-3° near the present day shelf margin. These borehole intersections provide the only direct age control for the sub-cropping formations, immediately below the main post-breakup unconformity in the offshore area (Maung and others, 1997).

Santos (1993) compiled geological profiles based on early Shell mapping along the coastal areas. Tied to Awaba-1, Awaba-2, and Jilliby Creek-1 wells these show that the Upper Permian Coal Measures thicken to the east offshore and attain an approximate thickness of 1600 m at the coast.

Boyd (1996) described the interpretation of high-resolution seismic data recorded close to the coastline in the offshore Newcastle area. The base of the Newcastle Coal Measures coincides with a distinctive reflection observed some 80-90 m below sea level, some 100 m offshore from Redhead. Based on correlations with adjacent bores this distinctive reflection is interpreted as the base of the Newcastle Coal Measures. Below this boundary, high resolution seismic indicates a 60 m thick transparent unit, interpreted as the Waratah Sandstone and the upper Dempsey Formation marine shales. Correlating these units seaward, Boyd (1996) interpreted the base of the Newcastle Coal Measures cropping out on the seabed approximately 1 km east of the coast, consistent with the interpretation of a restricted distribution of this unit in the offshore.

The seismic stratigraphy further east is characterised by alternating units of multiple high amplitude reflections and transparent units each 10 - 50 m thick. This character is typical of coal measure sequences, and Maung and others (1997) interpreted offshore extensions of the Tomago Coal Measures as subcropping at the post-breakup unconformity around 5 km seaward of the coastline. The deepest coal seam in the Tomago Coal Measures in the Newcastle region is around 900 m below the surface. On the offshore seismic data, this depth is approximately coincident to where a change in seismic style is observed between high frequency, continuous high amplitude seismic reflections (Tomago Coal Measures) and lower frequency less continuous seismic reflections, interpreted as the Maitland Group (Maung and others, 1997). This interpretation suggests that the Maitland Group subcrops beneath the post-breakup unconformity on the shelf between the subcrop edge of the Tomago Coal Measures and the Offshore Uplift. Deeper units such as the Greta Coal Measures do not subcrop at this unconformity level across the Offshore Syncline east of Newcastle. Similarly, these correlations infer that Triassic sediments are preserved as the Offshore Syncline plunges southwards, and not adjacent to the northern Sydney Basin. On Figure 37 Maung and others (1997) interpreted the Tomago Coal Measures to have been truncated by the western bounding fault of the Offshore Uplift. Compression has up-turned the synclinal sequences and subsequent erosion truncated their distribution so that today their distribution is confined to areas within the Syncline (Figures 37, 38).

# Figure Captions

| | |
|---|---|
| Figure 1 | Location of sedimentary basins covered by this report. |
| Figure 2 | Digital elevation and bathymetry of the area covered by this report. |
| Figure 3 | Gravity map of the central east coast area. |
| Figure 4 | Magnetic map of the central east coast area. |
| Figure 5 | Tectonic elements and petroleum discoveries, Sydney Basin. (After Maung and others, 1997.) |
| Figure 6 | Sydney Basin offshore industry seismic lines and some onshore well locations. (After Maung and others, 1997.) |
| Figure 7 | Sydney Basin stratigraphy. (After Maung and others, 1997.) |
| Figure 8 | Sydney Basin cross section, showing schematic stratigraphic relationships of the Permian sequence. (After Maung and others, 1997.) |
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| Figure 17 | Composite cross section (4:1 exaggeration) across Mesozoic sedimentary basins of easternmost Australia showing |

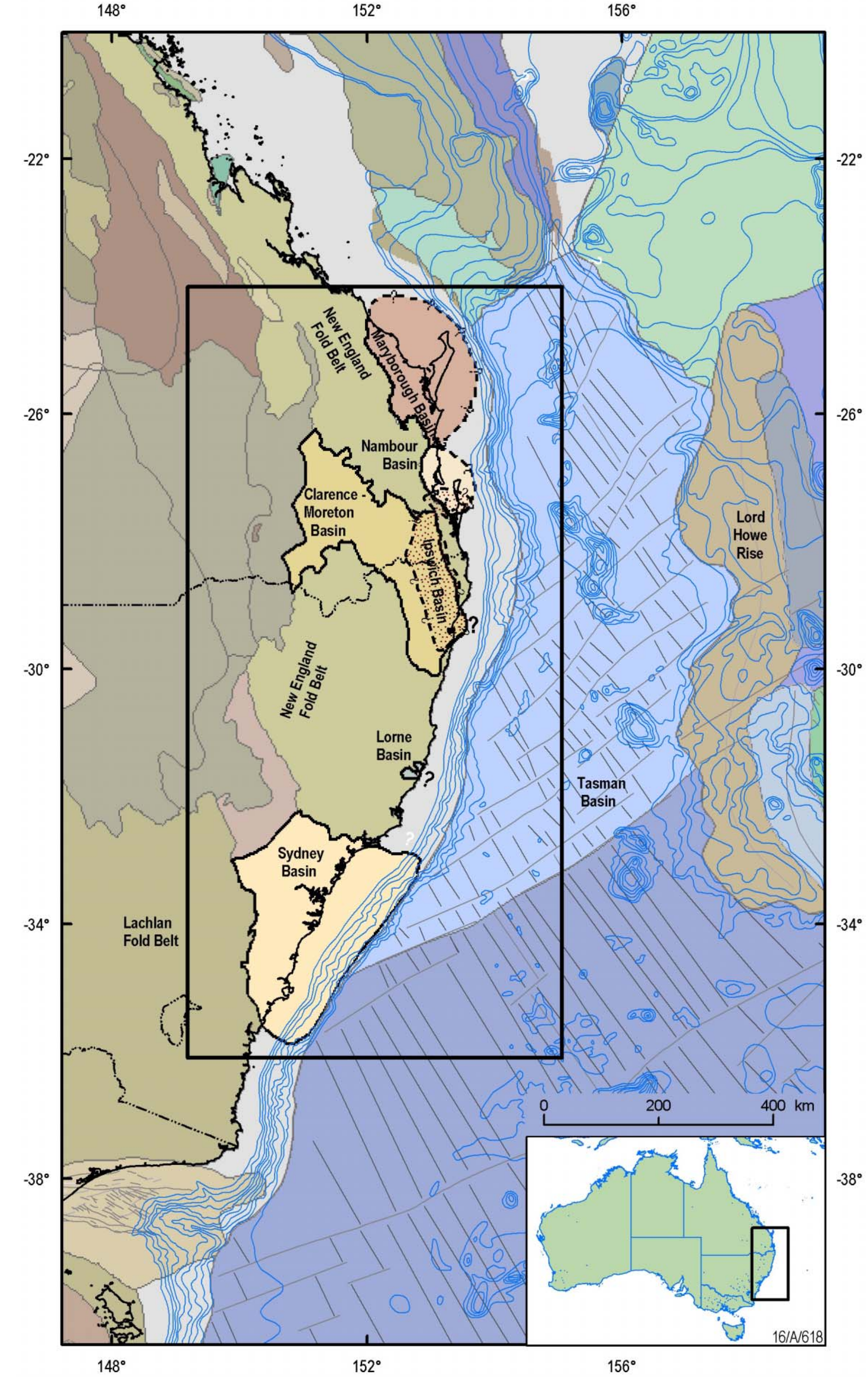


Figure 1. Location of sedimentary basins covered by this report

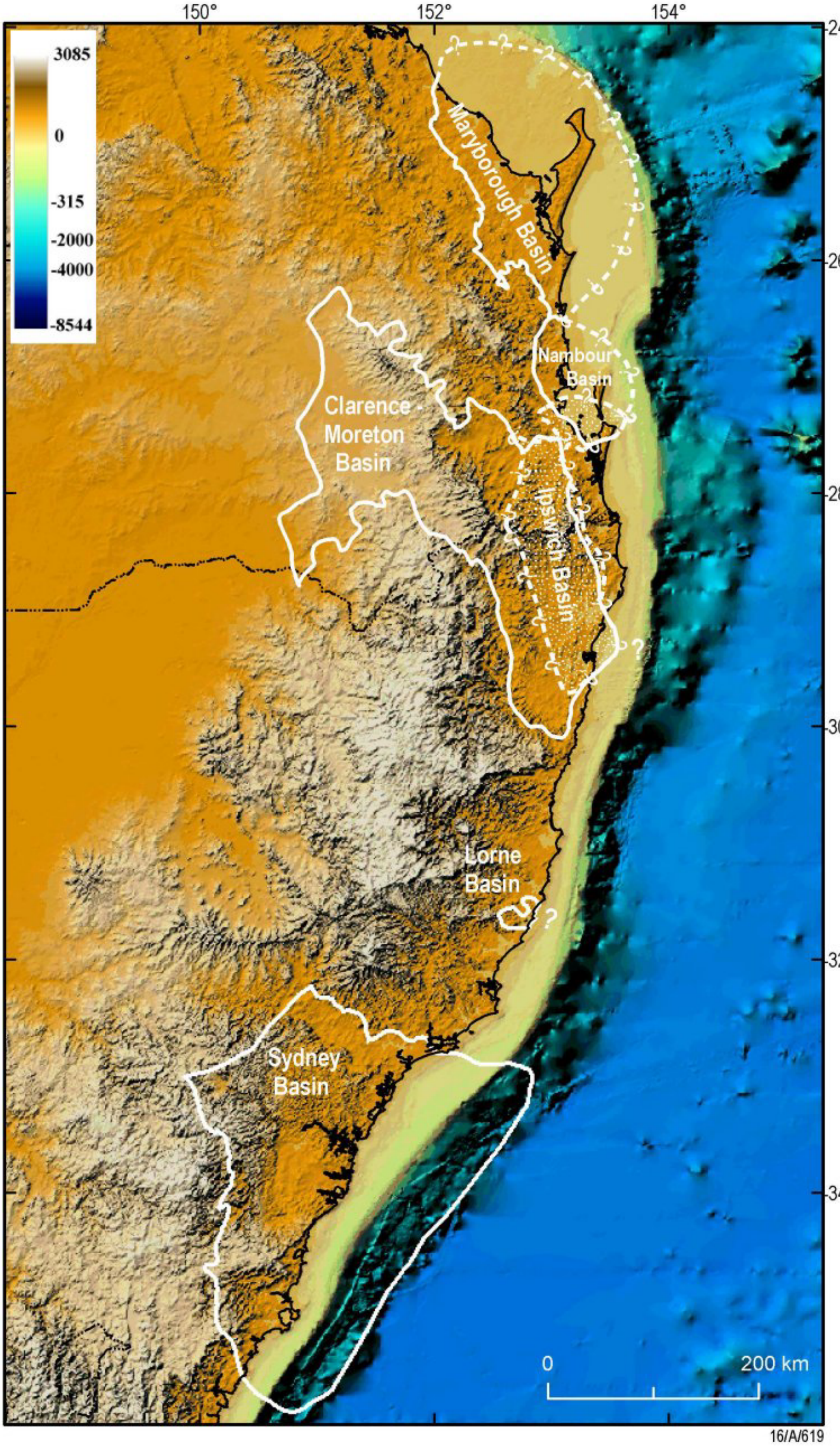


Figure 2. Digital elevation and bathymetry of the area covered by this report

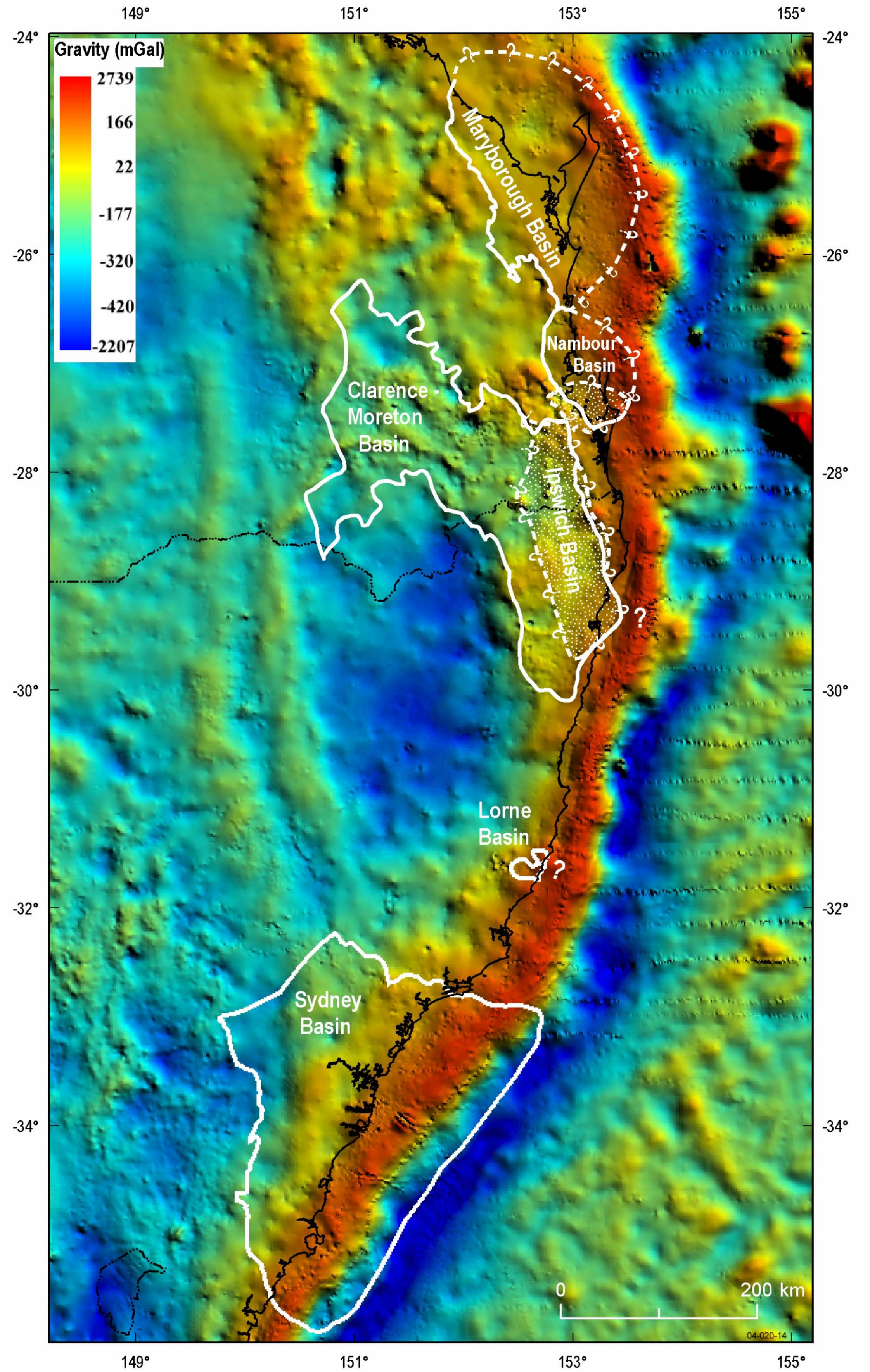


Figure 3. Gravity map of the central east coast area

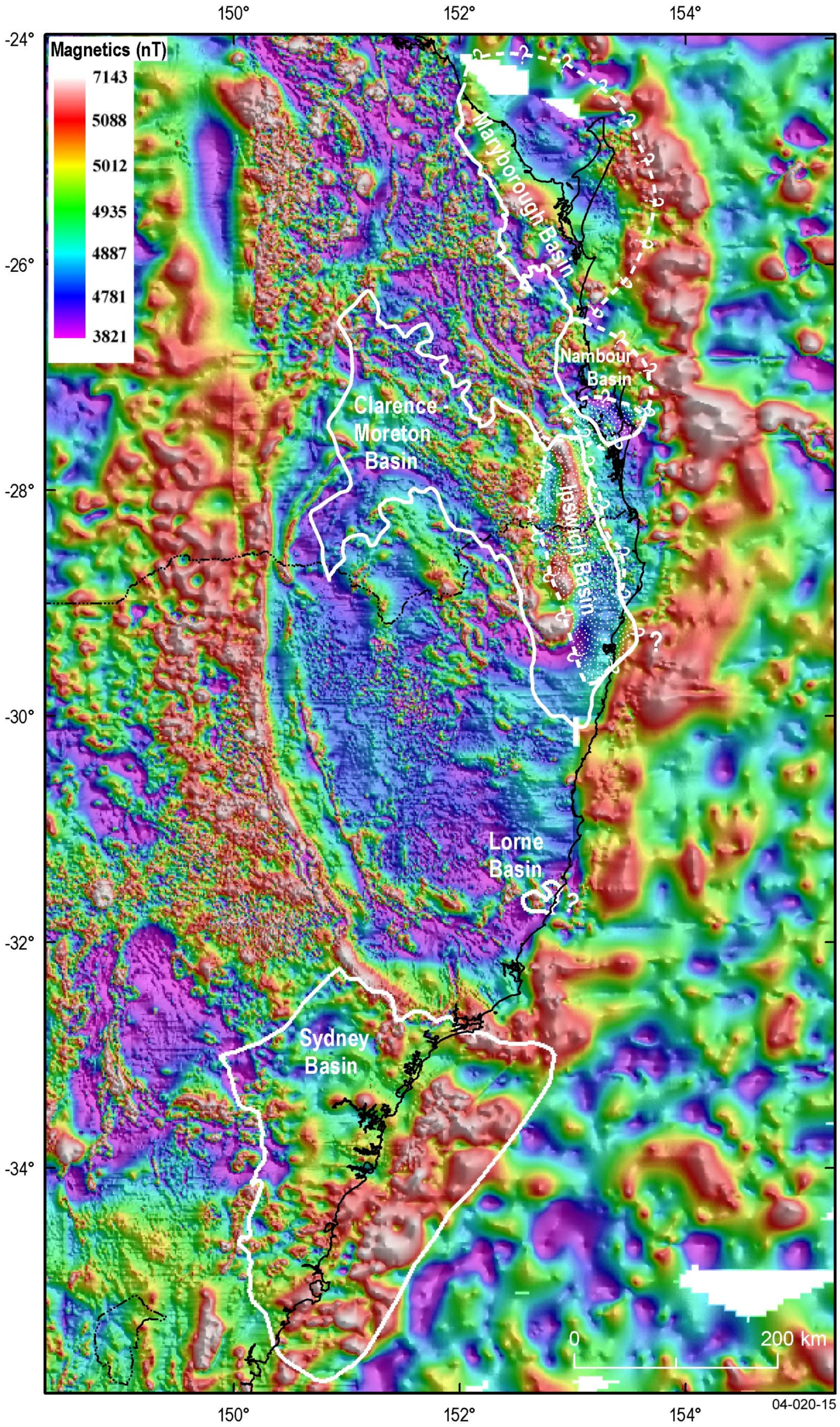


Figure 4. Magnetic map of the central east coast area

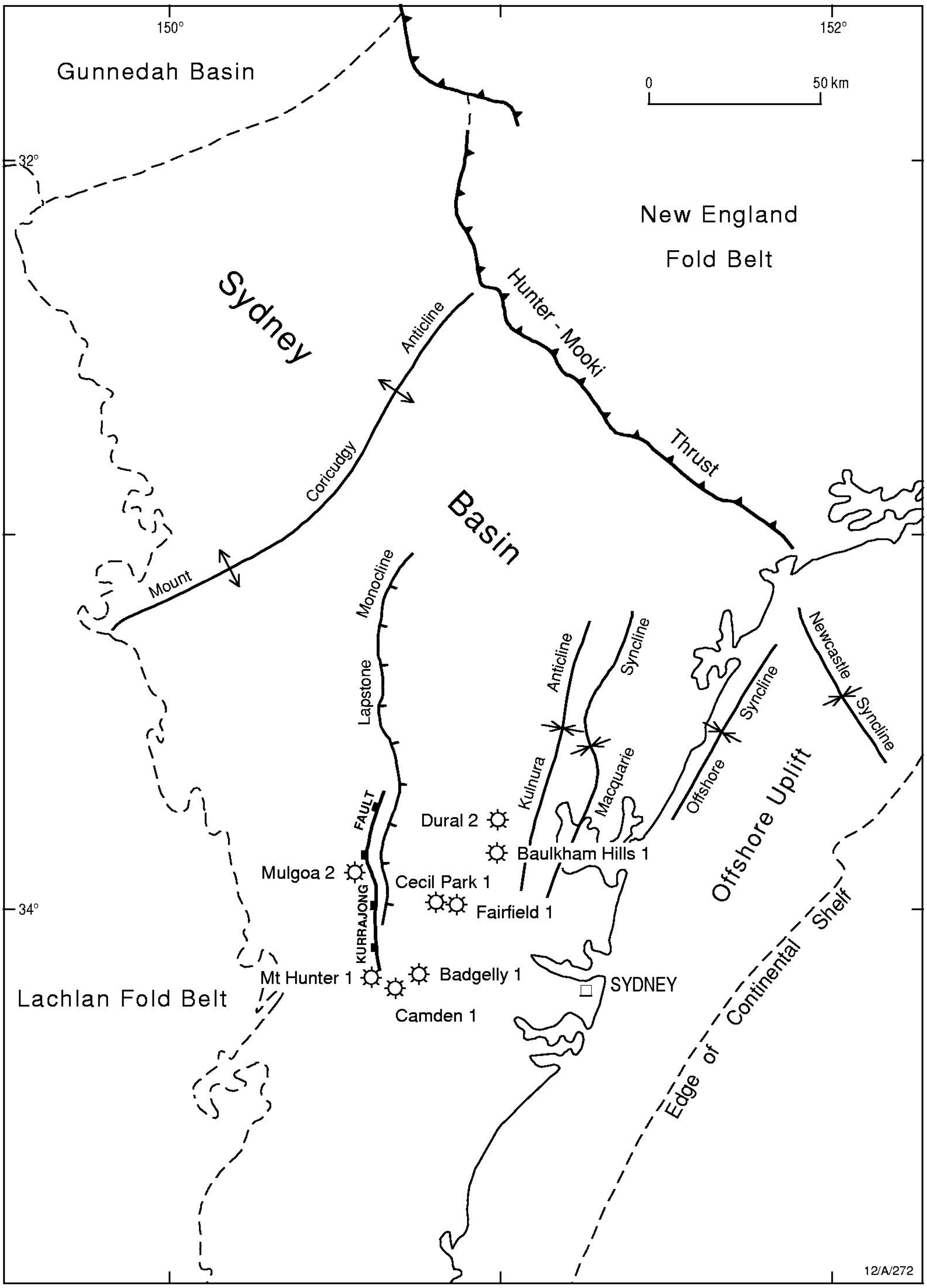


Figure 5. Tectonic elements and petroleum discoveries, Sydney Basin. (After Maung and others, 1997.)

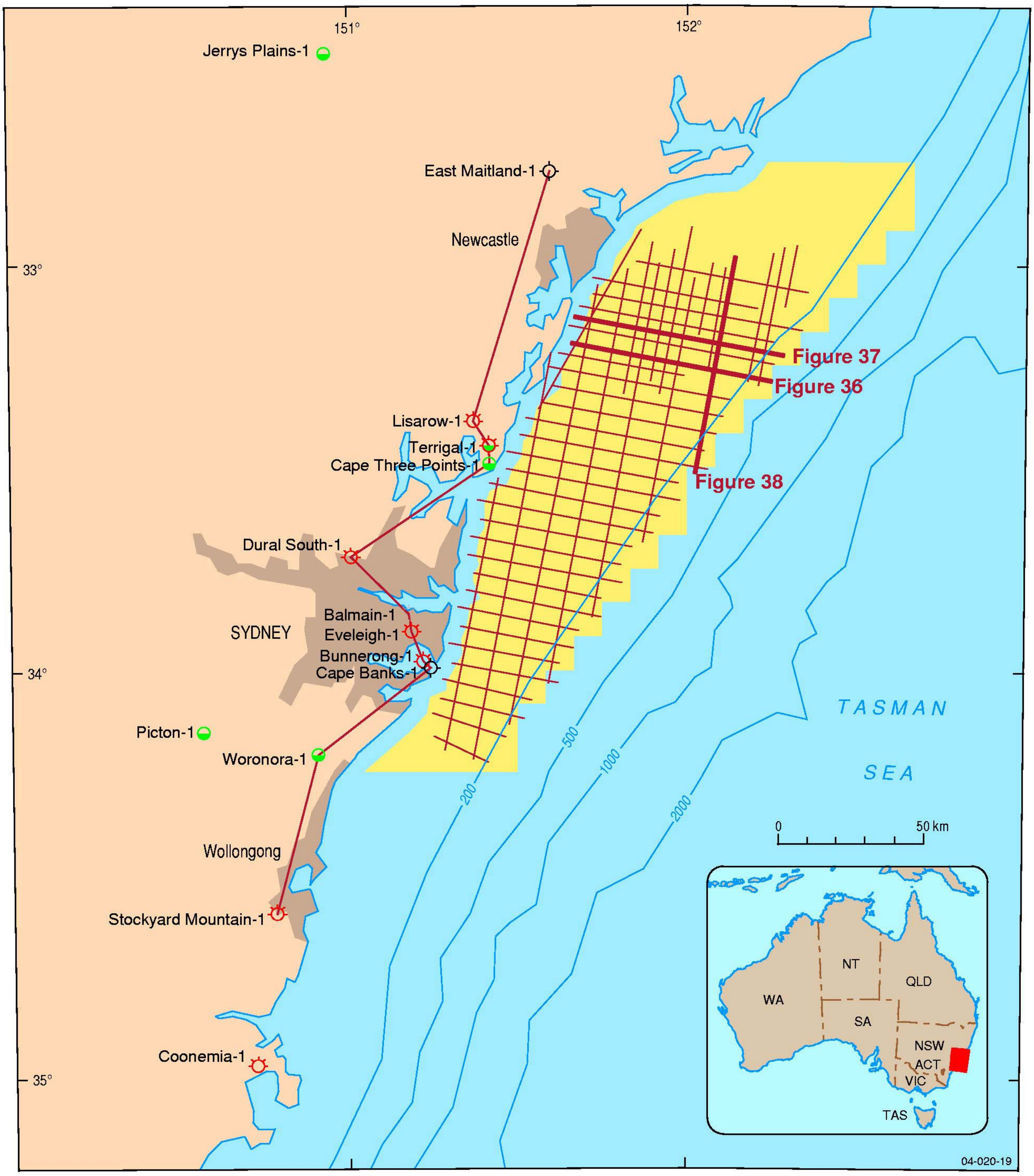


Figure 6. Sydney Basin offshore industry seismic lines and some onshore well locations. (After Maung and others, 1997.)

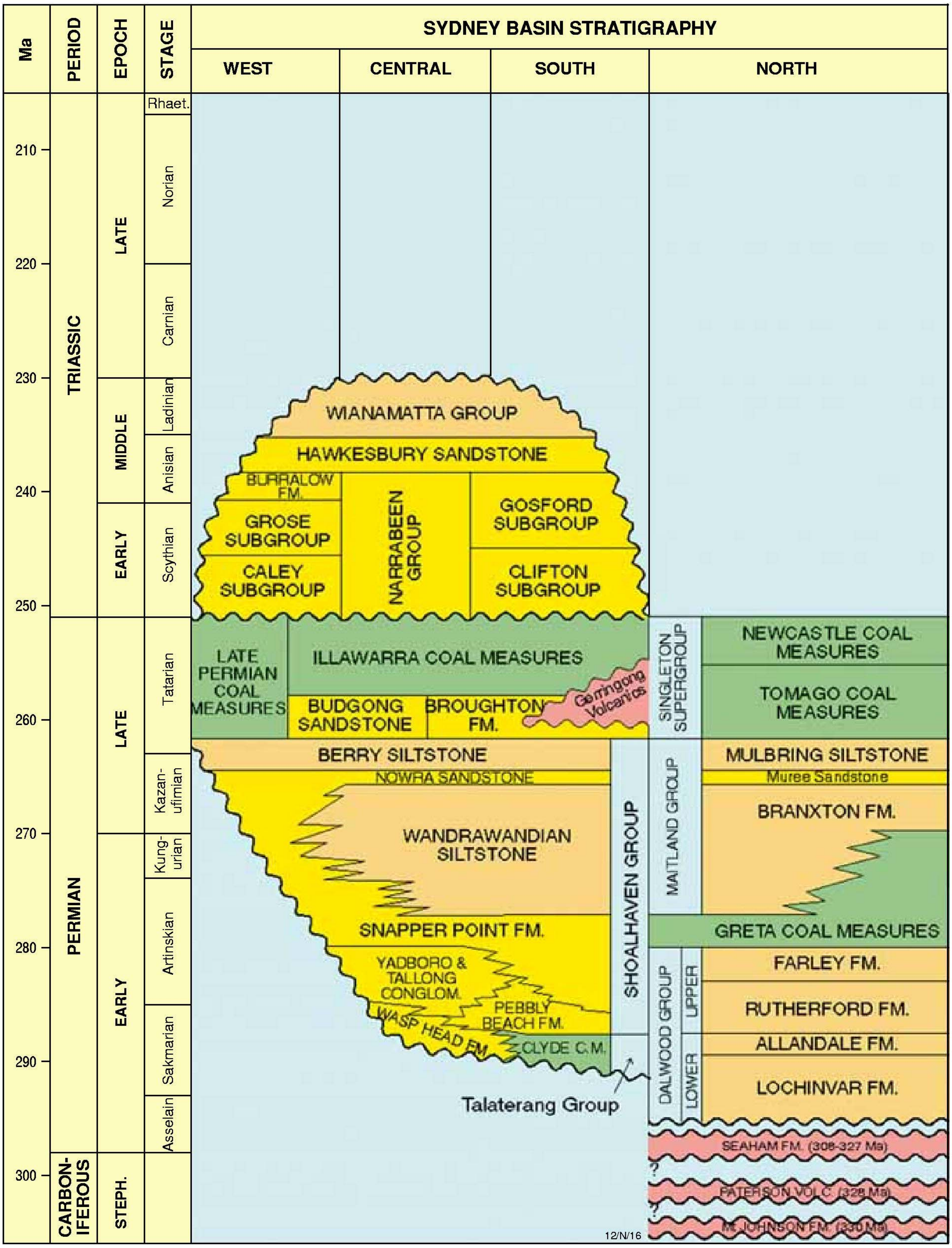


Figure 7. Sydney Basin stratigraphy. (After Maung and others, 1997.)

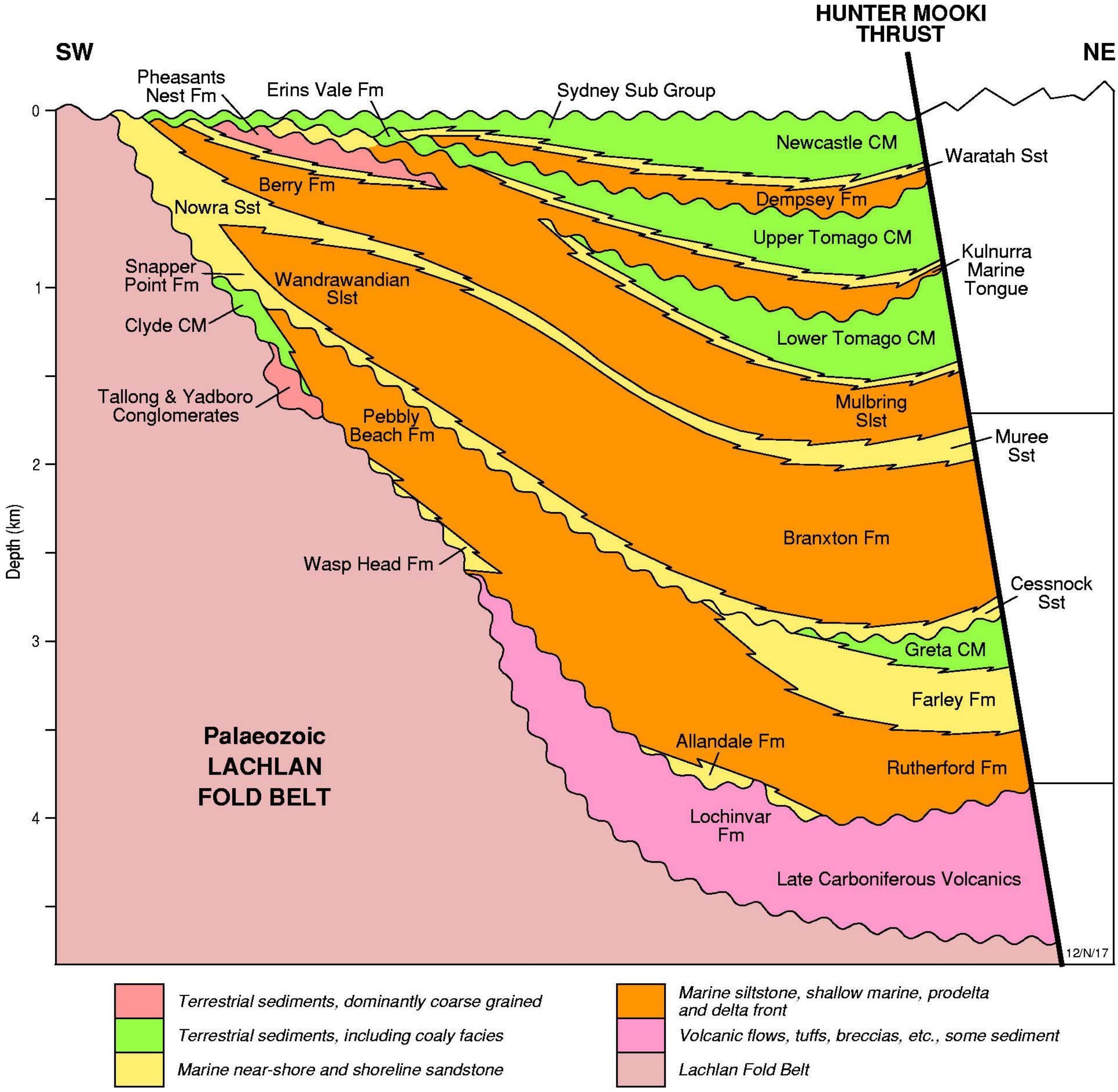


Figure 8. Sydney Basin cross section, showing schematic stratigraphic relationships of the Permian sequence. (After Maung and others, 1997.)

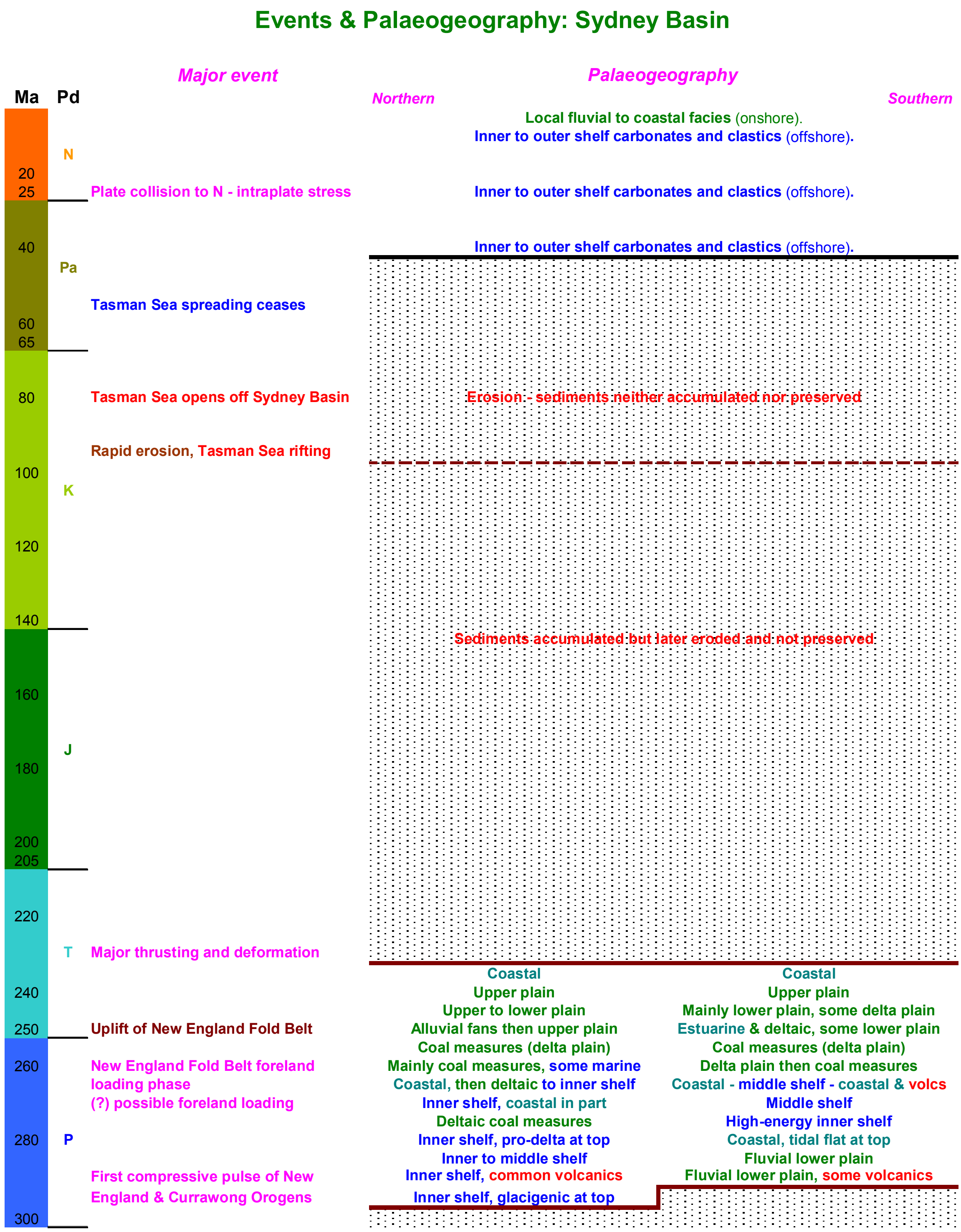


Figure 9. Major events and palaeogeography, Sydney Basin

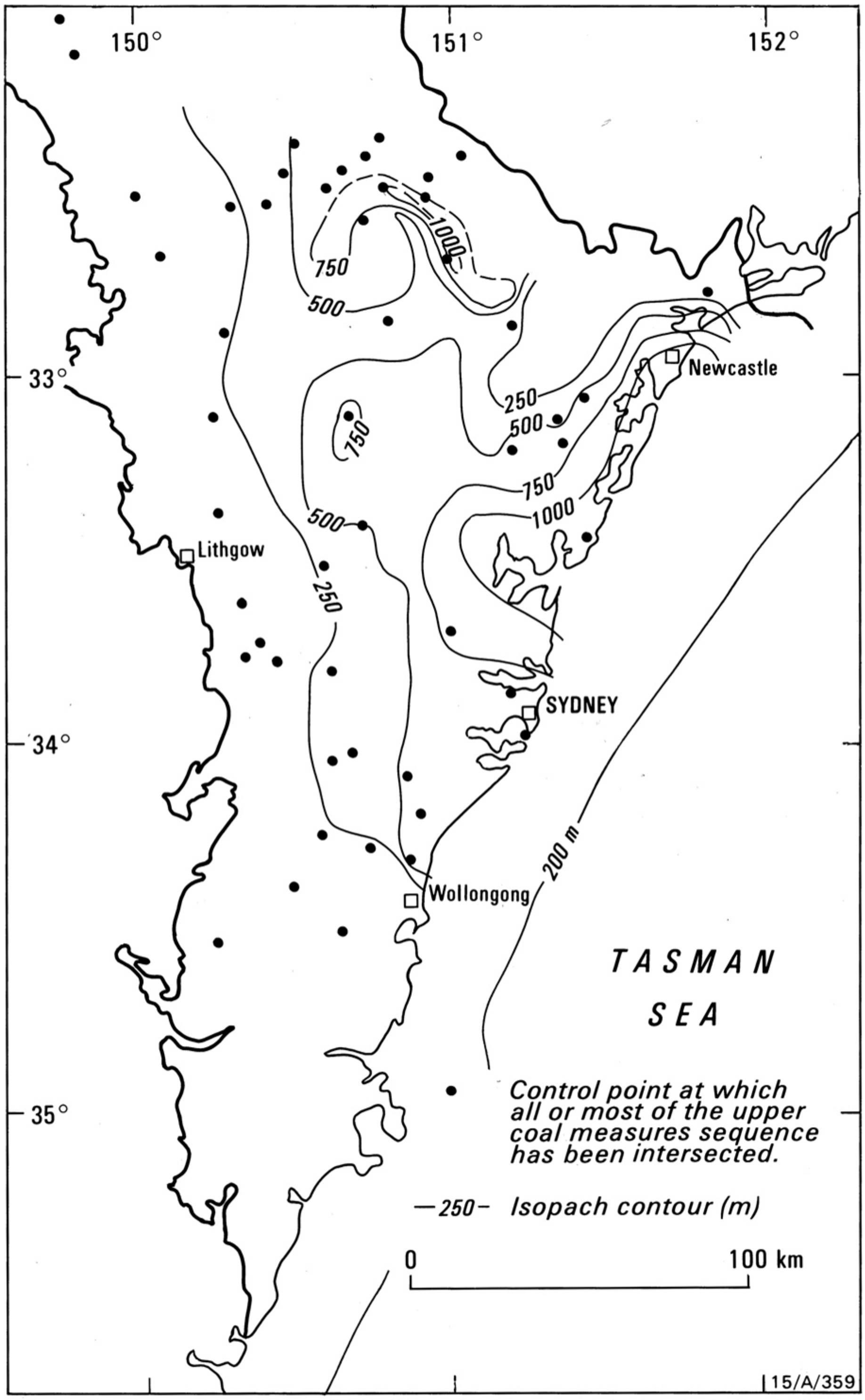


Figure 10. Isopachs of the upper coal measures, Sydney Basin (Newcastle and Tomago Coal Measures, Singleton Supergroup, and Illawarra Coal Measures). (After Brakel, 1983.)

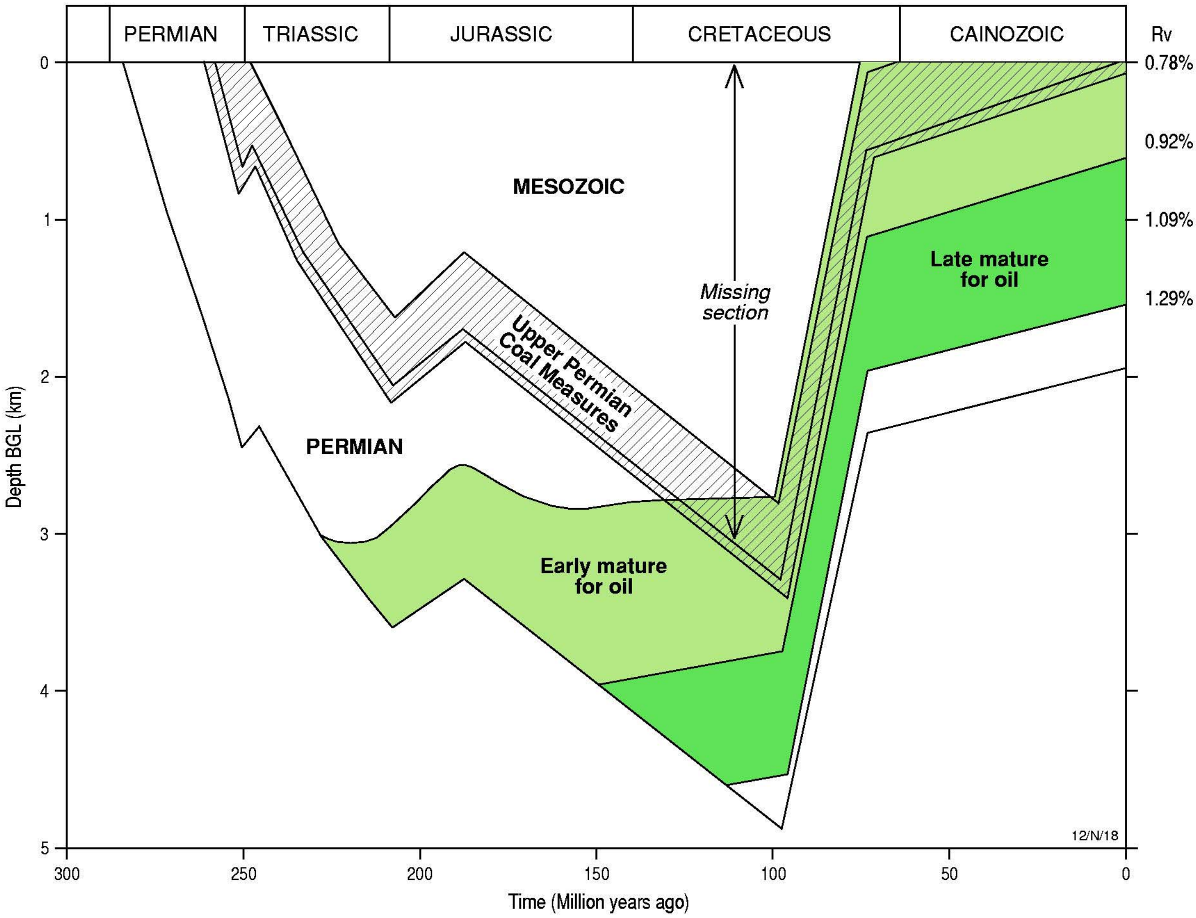


Figure 11. Sydney Basin generalised burial history curve. (After Grybowski, 1992.)

## Petroleum Systems Summary - Sydney Basin

> 100 onshore, 0 offshore wells

*Northern area*

| Period | Rock unit | Source | Reservoir | Seal | Shows |
|---|---|---|---|---|---|
| TR | (not preserved) | | | | |
| TR | Wianamatta Group | | OIL & GAS | regional | |
| TR | Hawkesbury Sandstone | | good | | gas,oil |
| TR | Narrabeen Group | ? | good | intraformational | gas,oil |
| TR | Narrabeen Group | ? | good | | gas,oil |
| P | Newcastle Coal Measures | oil window | OIL & GAS | | gas,oil |
| P | Tomago Coal Measures | oil window | intraformational | intraformational | gas |
| P | Mulbring Siltstone | (?) late oil window | gas, minor oil | regional | gas,oil |
| P | Muree Sandstone | | diagenesis risk | | minor |
| P | Branxton Formation | (?) late oil window | gas | regional | gas |
| P | Greta Coal Measures | overmature for oil | intraformational | intraformational | oil |
| P | Farley Formation | gas | poor | | minor |
| P | Rutherford Formation | gas | gas | regional | minor |
| P | Lower Dalwood Group | | poor | | oil |

*Southern area*

| Period | Rock unit | Source | Reservoir | Seal | Shows |
|---|---|---|---|---|---|
| TR | (not preserved) | | | | |
| TR | Wianamatta Group | | GAS | regional | |
| TR | Hawkesbury Sandstone | | good | | gas,oil |
| TR | Gosford Subgroup | ? | GAS | intraformational | gas,oil |
| TR | Clifton Subgroup | ? | good | | gas,oil |
| P | Illawarra Coal Measures | overmature for oil | intraformational | intraformational | gas |
| P | Budgong Sandstone & eq. | | diagenesis risk | | |
| P | Berry Siltstone | gas | gas | regional | gas,oil |
| P | Nowra Sandstone | | diagenesis risk | | minor |
| P | Wandrawandian Siltstone | gas | gas | regional | gas |
| P | Snapper Point Formation | | diagenesis risk | | gas |
| P | Pebbley Beach Fm & equiv. | gas | poor | intraformational | minor |
| P | Clyde Coal Measures & eq. | gas | poor | | |

Figure 12. Petroleum systems summary, Sydney Basin

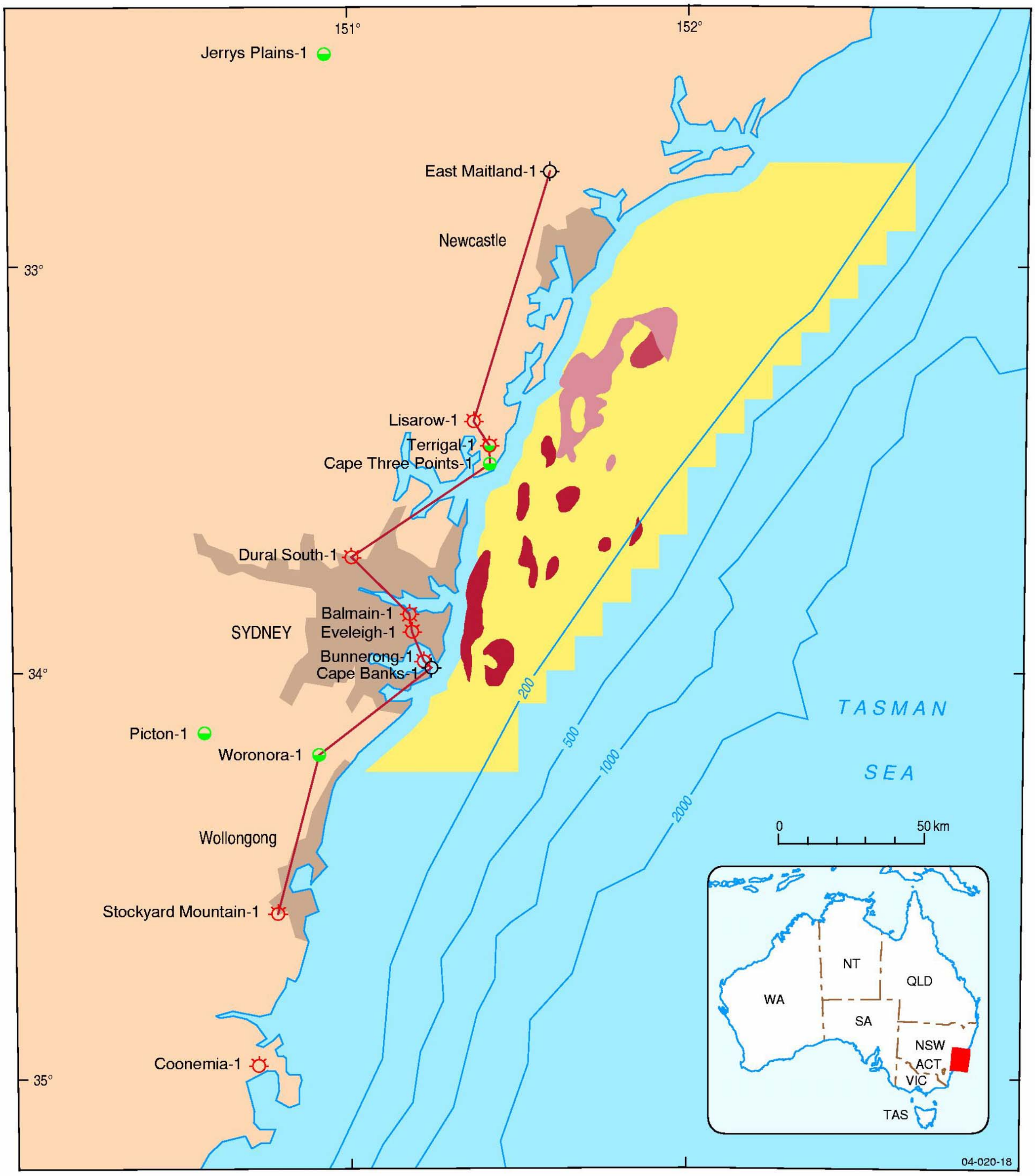


Figure 13. Offshore Sydney Basin structural fairways and leads. (After Maung and others, 1997.)

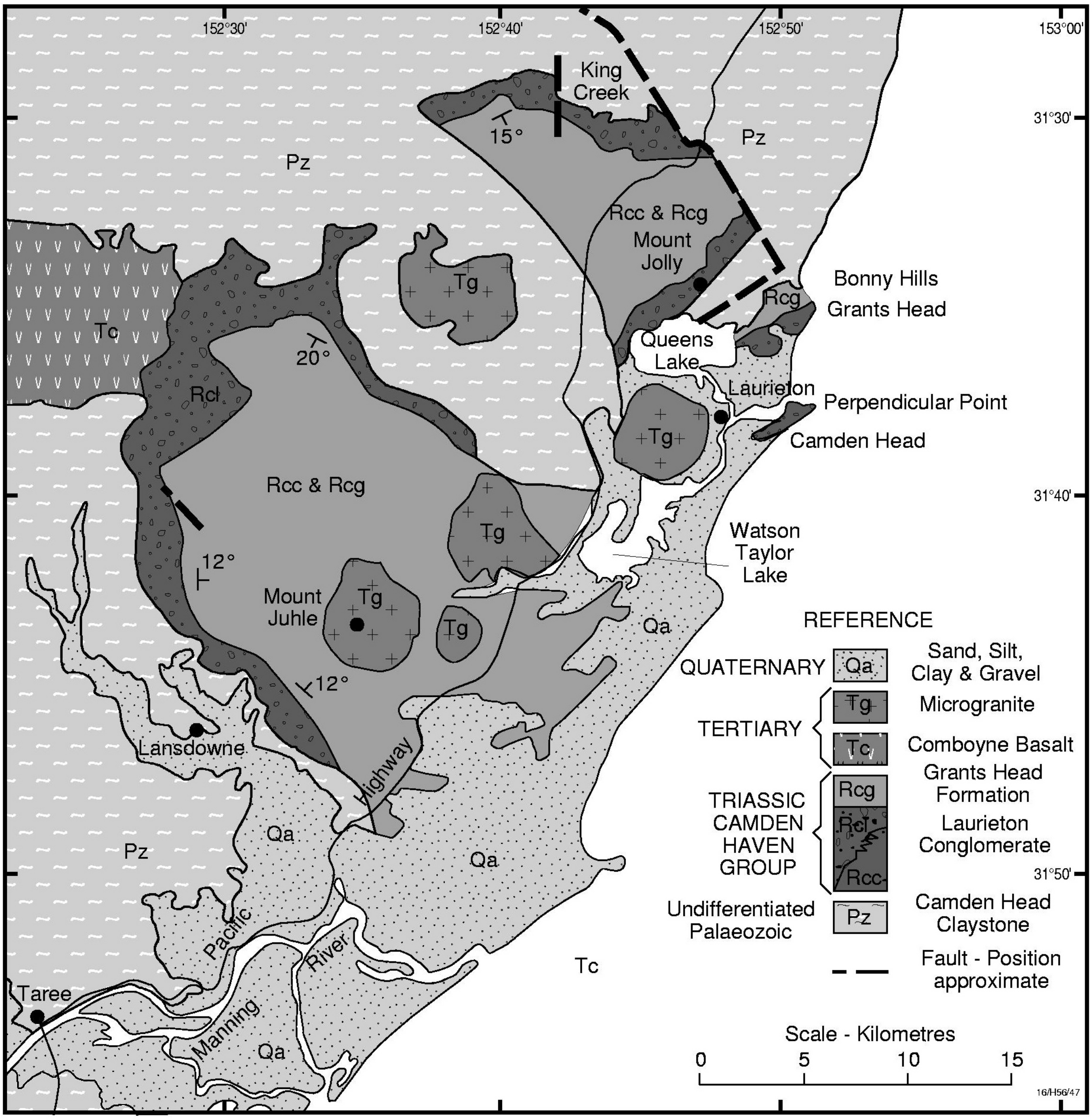


Figure 14. Generalised geological map of the Lorne Basin. (After Pratt and Herbert, 1973.)

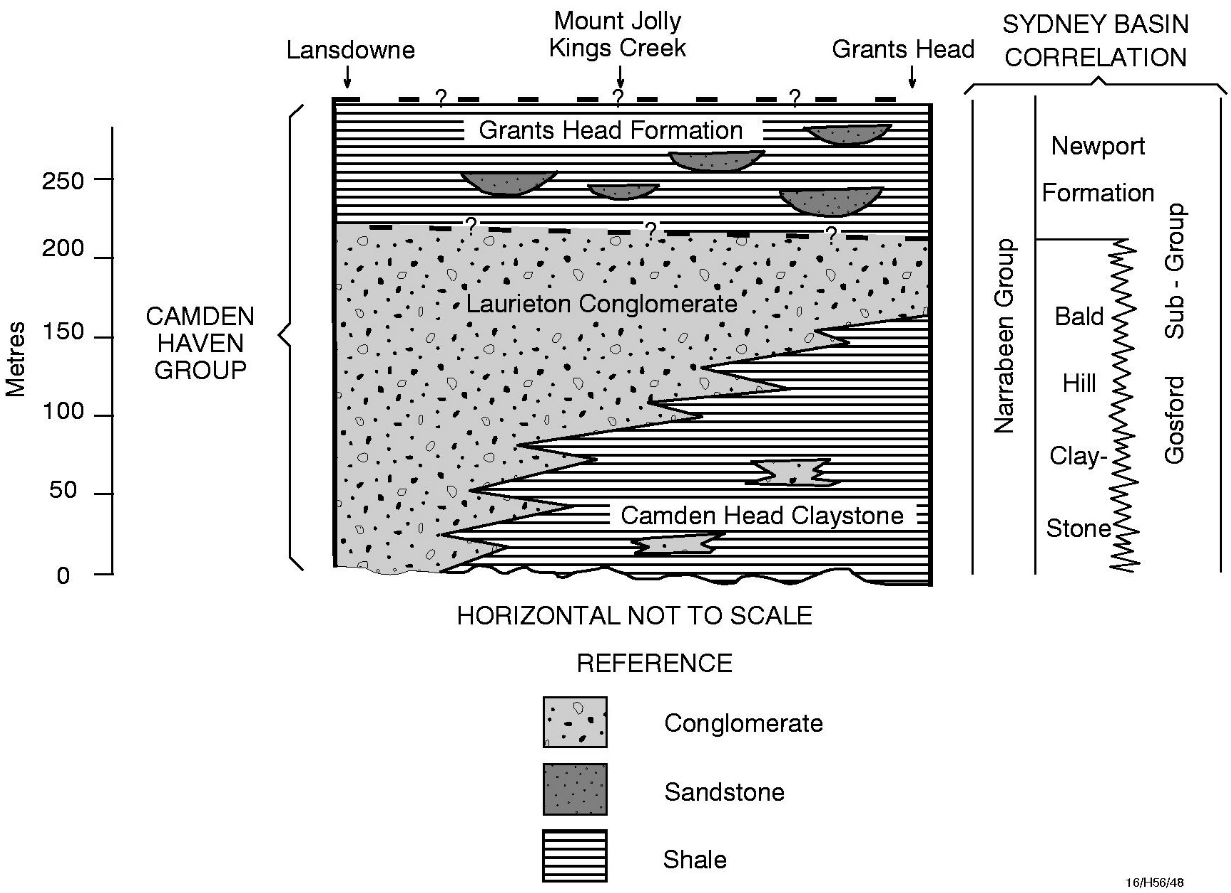


Figure 15. Stratigraphy of the Lorne Basin. (After Pratt and Herbert, 1973.)

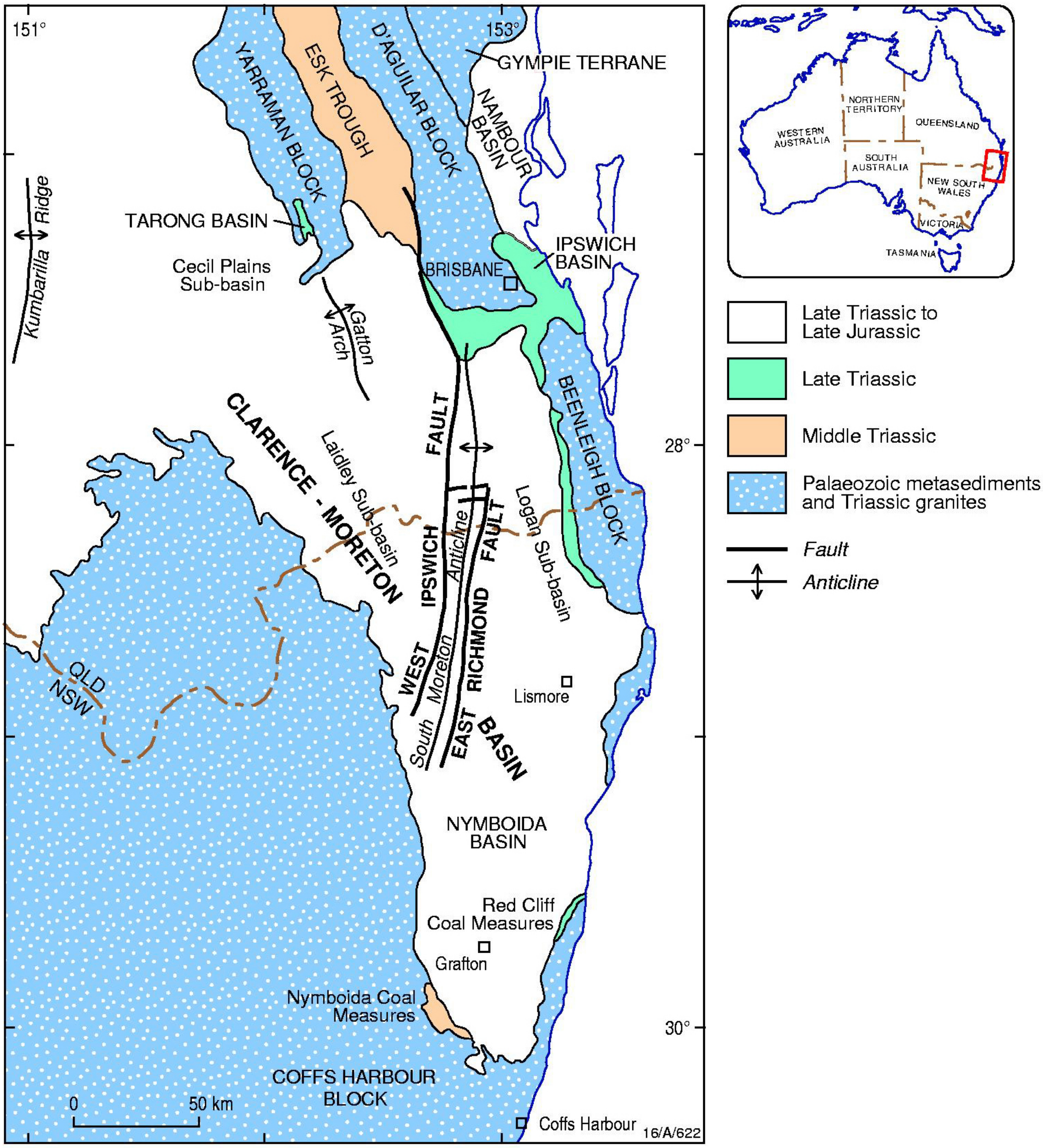


Figure 16. Regional geological setting of the Nymboida, Ipswich, Nambour and Clarence-Moreton Basins. (After O'Brien and others, 1994.)

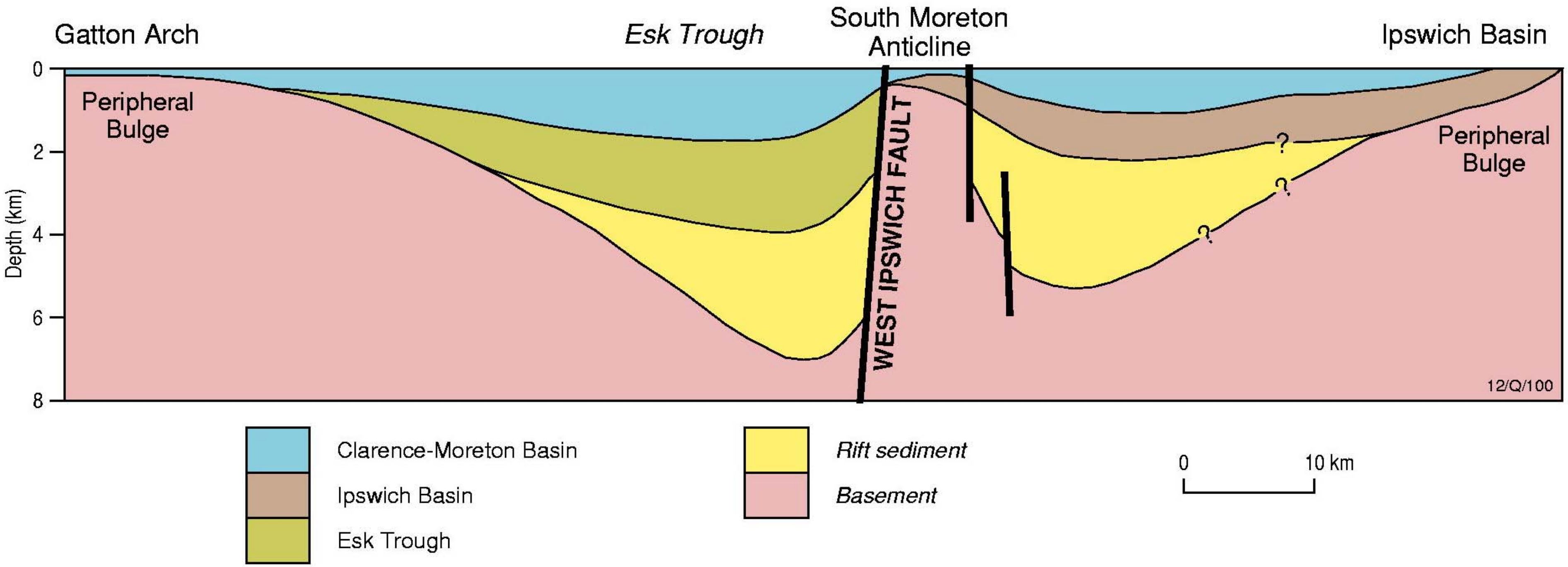


Figure 17. Composite cross section (4:1 exaggeration) across Mesozoic sedimentary basins of easternmost Australia showing interpreted geometries of basins and basement highs. The eastern half of the section steps to the south where the structure of the western margin of the Ipswich Basin is more clearly defined. (After Korsch and others, 1989.)

| AGE | STRATIGRAPHIC UNIT | THICKNESS | LITHOLOGY | FACIES | DEPOSITIONAL ENVIRONMENT |
|---|---|---|---|---|---|
| ? CRETACEOUS LATE JURASSIC | GRAFTON FORMATION | 150–250 m | *Sandstone, clayey siltstone, minor claystone, coal* | *Sandy channel-fill, overbank/ flood plain deposits* | *Low-energy, mixed-load, meandering fluvial system, poss. terrestrial lakes* |
| | KANGAROO CREEK SANDSTONE | 200–?500 m | *Quartzose, cross-bedded sandstone* | *Sandy channel fill* | *Bed load fluvial system (braided stream)* |
| MIDDLE JURASSIC | Maclean Sandstone Member | 10–50 m | *Feldspathic sandstone* | *Sandy channel fill, lesser overbank dep.* | *Bed load meandering fluvial system* |
| | WALLOON COAL MEASURES | 30–400 m | *Interbedded sandstone, siltstone, claystone, coal, ironstone nodules* | *Sandy channel fill, with overbank and flood plain deposits, some backswamp facies* | *Mixed load meandering fluvial system* |
| EARLY JURASSIC | BUNDAMBA GROUP – MARBURG SUBGROUP: KOUKANDOWIE FORMATION | ?50–400 m | *Interbedded sandstone, siltstone, claystone, coal* | *Overbank/flood plain deposits, sandy splays channel fill* | *Mixed load, meandering fluvial system* |
| | Heifer Cr Sandstone Member | 10–50 m | *Coarse quartz sandstone, granite conglomerate* | *Channel fill* | *Bed load fluvial system* |
| | Ma Ma Cr Member | 10–50 m | *Interbedded sst, mudstone* | *Overbank/ flood plain facies* | *Mixed fluvial, lacustrine system* |
| | Towallum Basalt | 10–50 m | *Vesicular basalt, volcaniclastics* | *Lavas, epiclastics* | *? Terrestrial-lacustrine* |
| | GATTON SANDSTONE | 200–600 m | *Sandstone, conglomerate, minor fossil wood* | *Channel fill* | *Bed load to mixed load fluvial system* |
| | Koreelah Cgl | 5–50 m | *Pebble-cobble conglomerate, sst.* | *Alluvial fan, channel fill* | *Alluvial fan to bed load fluvial system* |
| | Calamia Member | 5–100 m | *Siltstone, claystone, sandstone* | *Flood plain/overbank facies* | *Mixed load fluvial system* |
| LATE TRIASSIC | BUNDAMBA GROUP – WOOGAROO SUBGROUP: RIPLEY ROAD SANDSTONE | 100–150 m | *Quartz sandstone, granule conglomerate* | *Channel fill* | *Bed load, braided fluvial system* |
| | RACEVIEW FORMATION | 0–250 m | *Interbedded sst., siltstone, claystone* | *Overbank/flood plain, with crevasse splays* | *Mixed load fluvial system* |
| | LAYTONS RANGE CONGLOMERATE | 0–80 m | *Conglomerate, minor sandstone* | *Alluvial fan* | *Alluvial fan system* |
| EARLY LATE TRIASSIC | IPSWICH COAL MEASURES: REDCLIFF COAL MEASURES | ? > 100 m | *Lithic conglomerate & breccia, sandstone, siltstone, coal* | *Alluvial fan, overbank/ flood plain deposits, interfan marshes* | *Alluvial fan-mixed load fluvial system* |
| | EVANS HEAD COAL MEASURES | ? > 50 m | *Sandstone, siltstone claystone, conglomerate, very minor coal* | *Channel fill, overbank/ flood plain deposits* | *Bed load to mixed load fluvial system* |
| MIDDLE TRIASSIC | NYMBOIDA COAL MEASURES | > 1000 m | *Sandstone, conglomerate, siltstone, claystone, coal, volcanics* | *Varied* | *Varied* |

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Figure 18. Stratigraphy of the Nymboida, Ipswich and Clarence-Moreton Basins. (After Willis, 1994.)

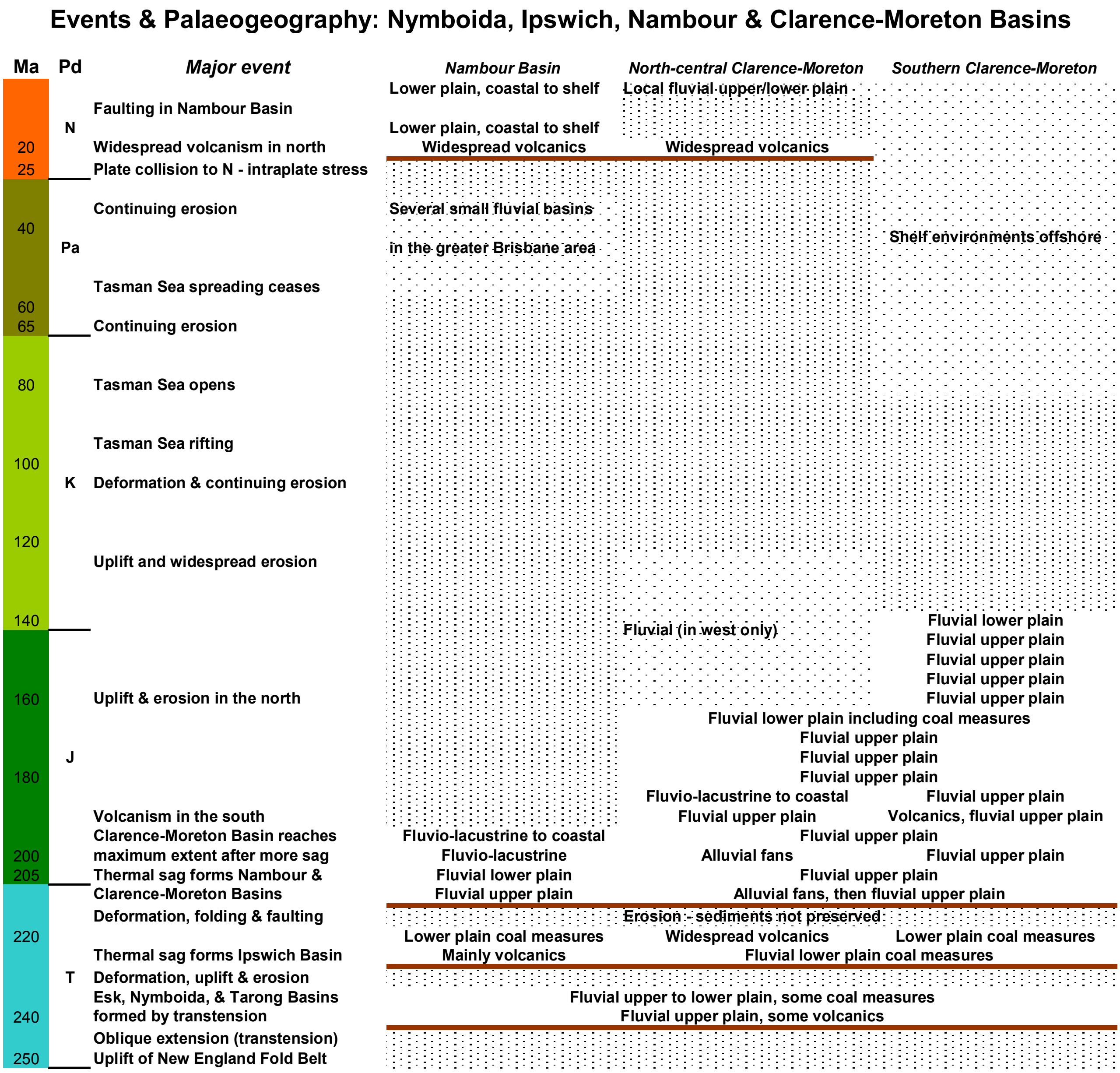


Figure 19. Major events and palaeogeography, Nymboida, Ipswich, Nambour and Clarence Moreton Basins

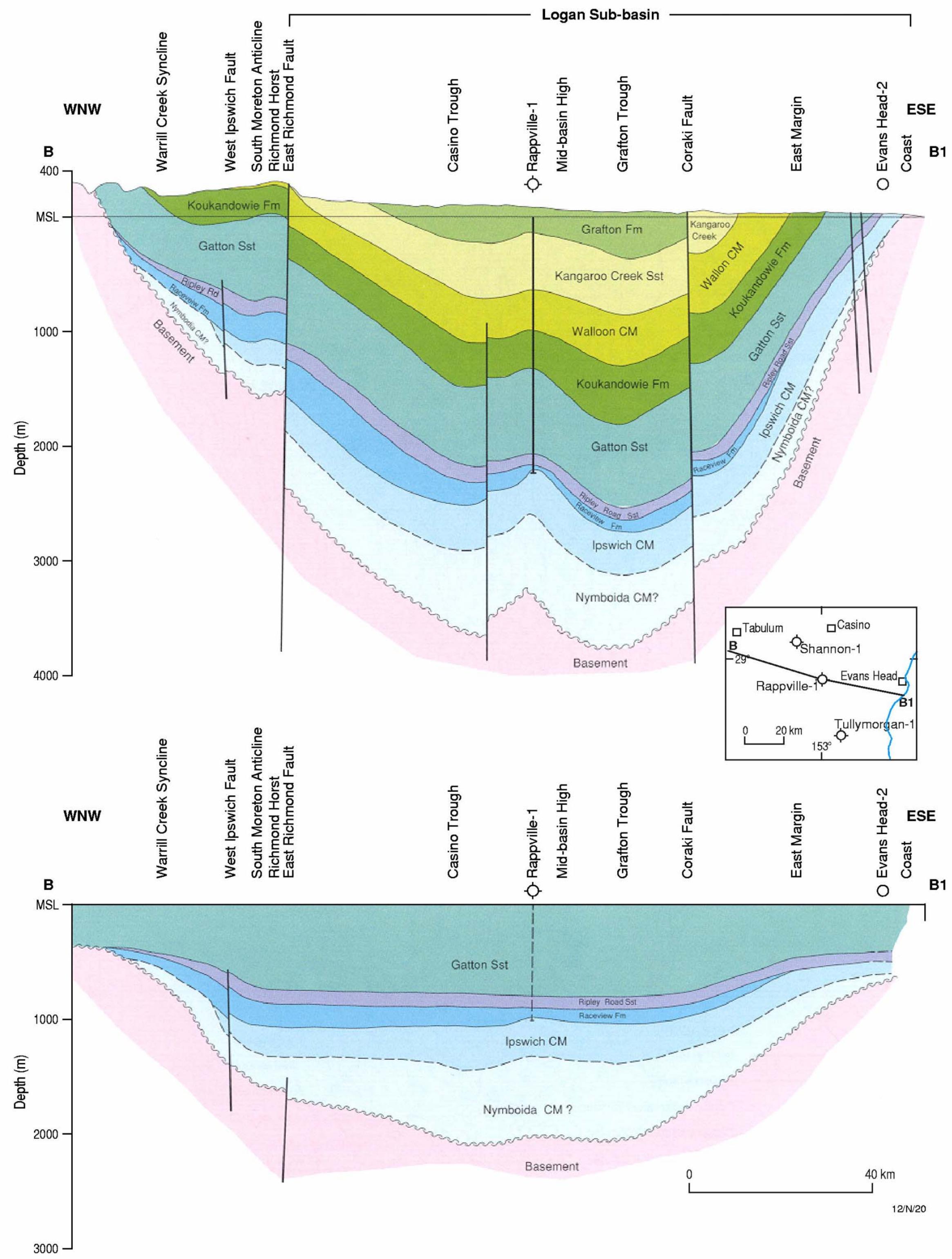


Figure 20. East-west structural cross-section across the central New South Wales portion of the Nymboida, Ipswich and Clarence-Moreton Basins, with a restored reconstruction on top Gatton Sandstone as a datum. (After Ingram and Robinson, 1996.)

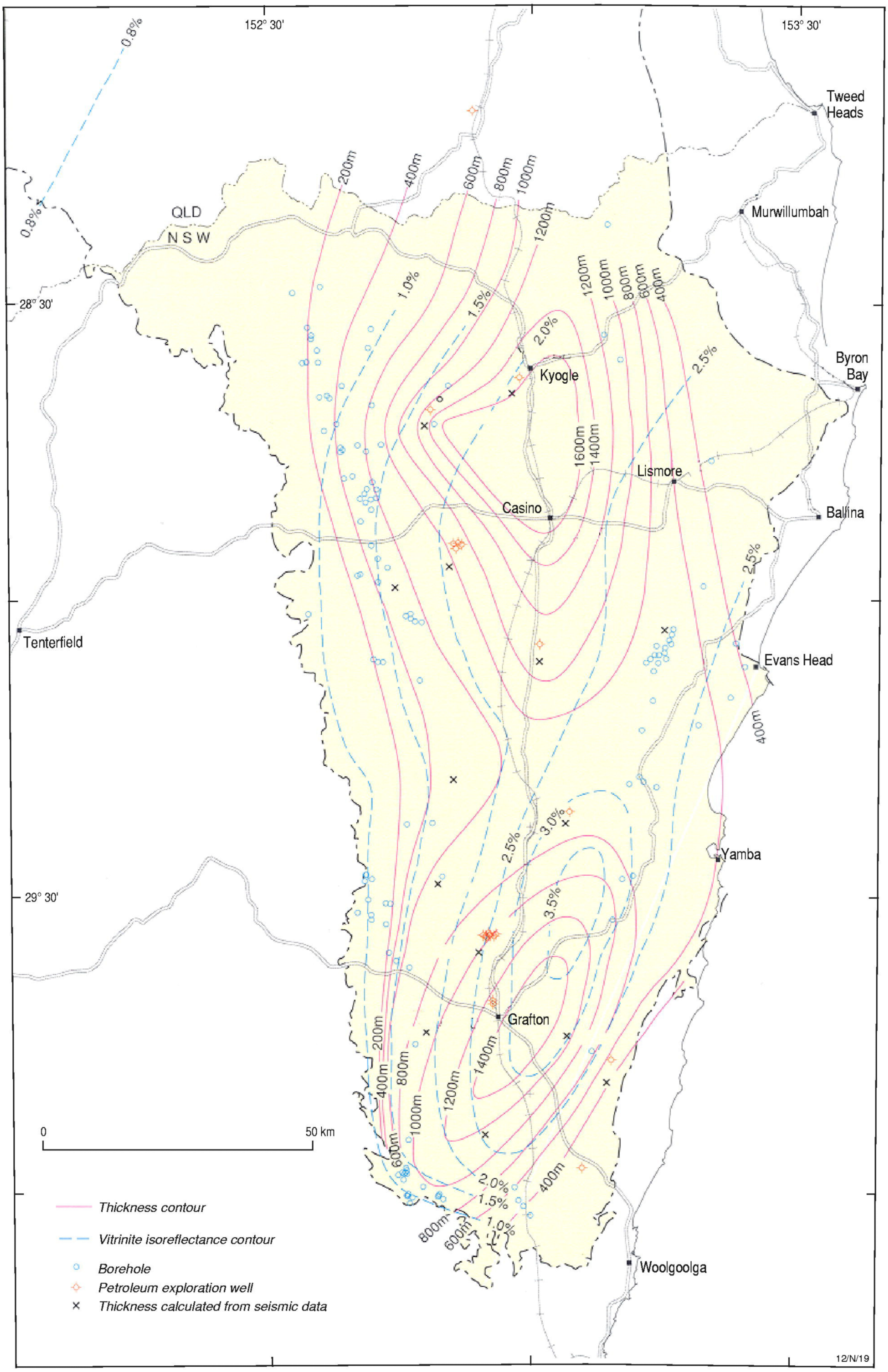


Figure 21. Combined thickness and vitrinite reflectances of the Nymboida Coal Measures (Nymboida Basin), Ipswich Coal Measures (Ipswich Basin) and Chillingham Volcanics (Clarence-Moreton Basin) in New South Wales. (After Ingram and Robertson, 1996.)

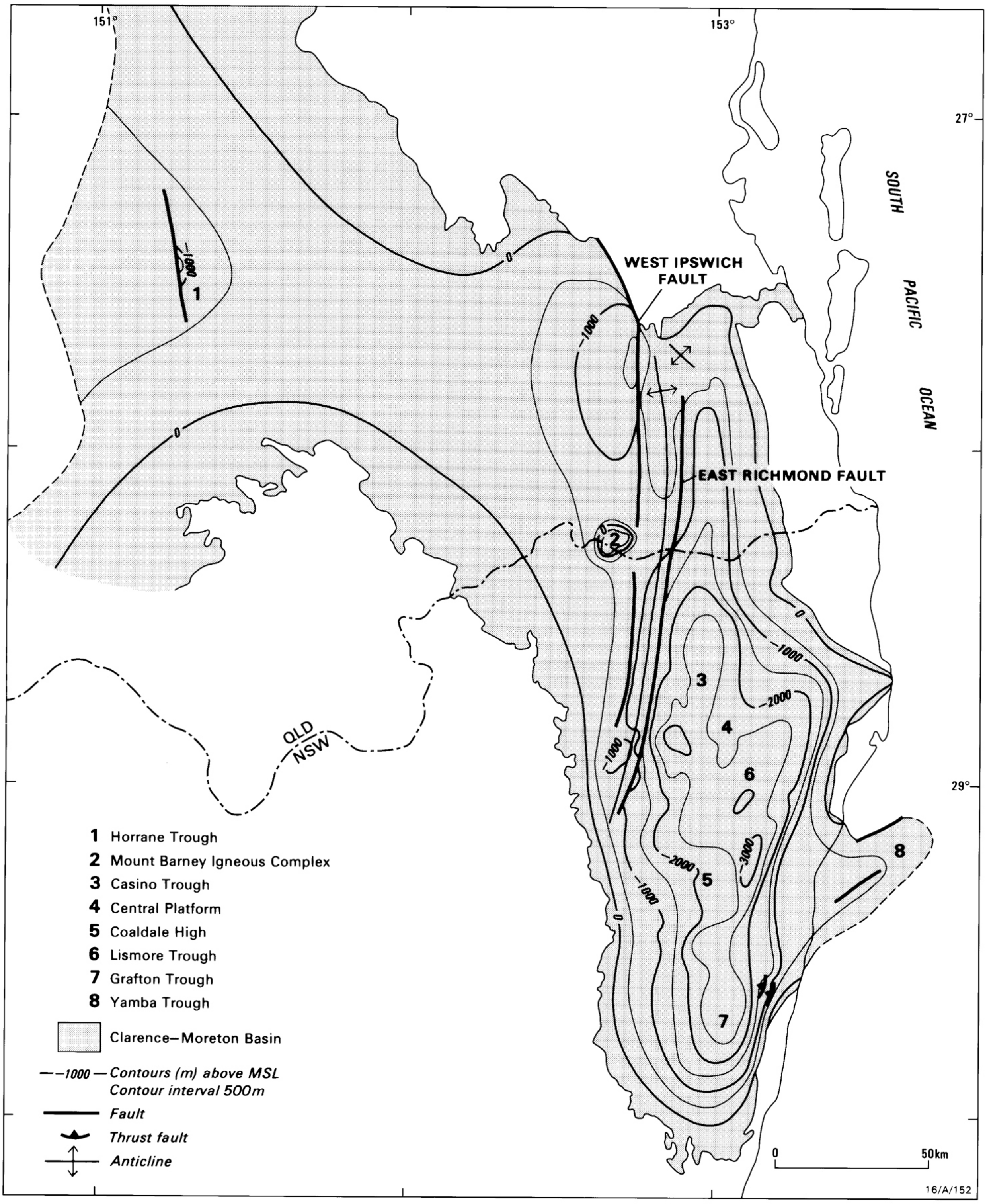


Figure 22. Generalised structure contour map of the base of the Clarence-Moreton Basin, showing features within the major sub-basins. (After Wells and O'Brien, 1994.)

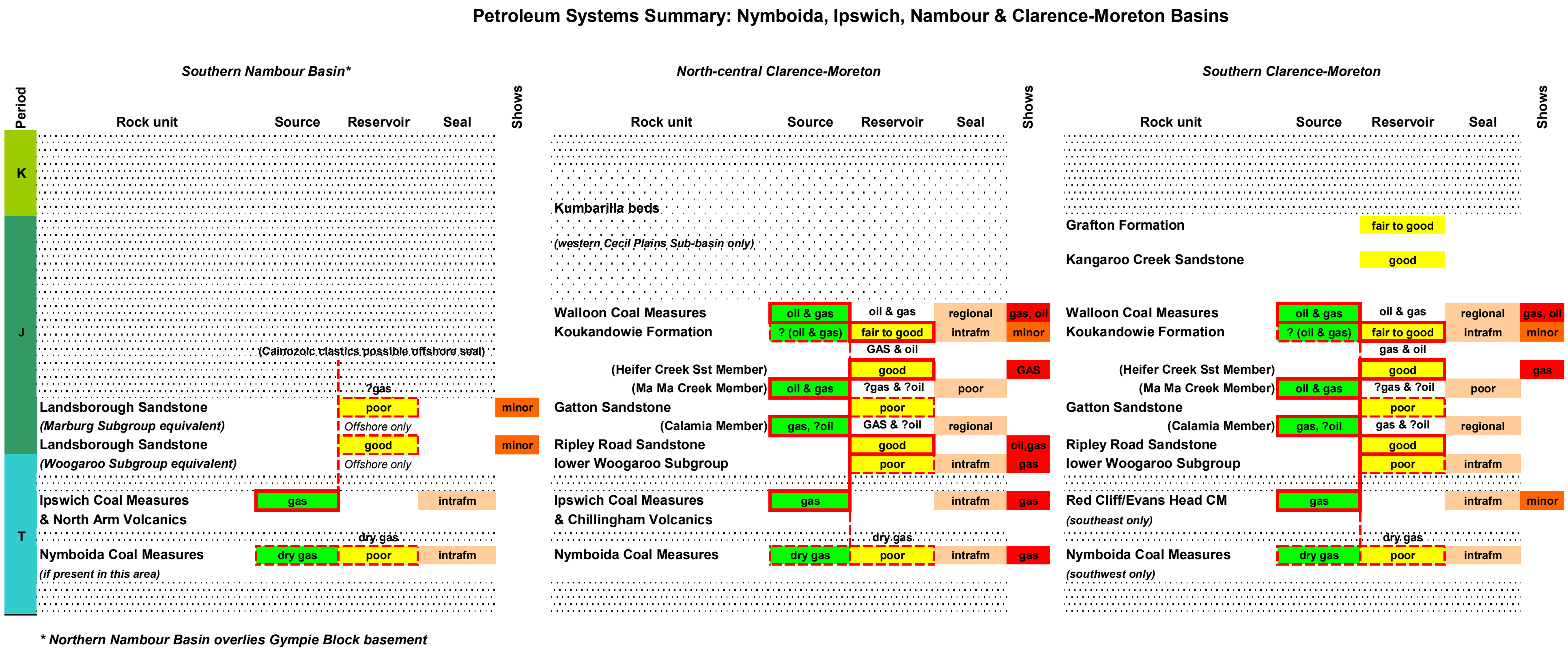


Figure 23. Petroleum systems summary, Nymboida, Ipswich, Nambour and Clarence-Moreton Basins

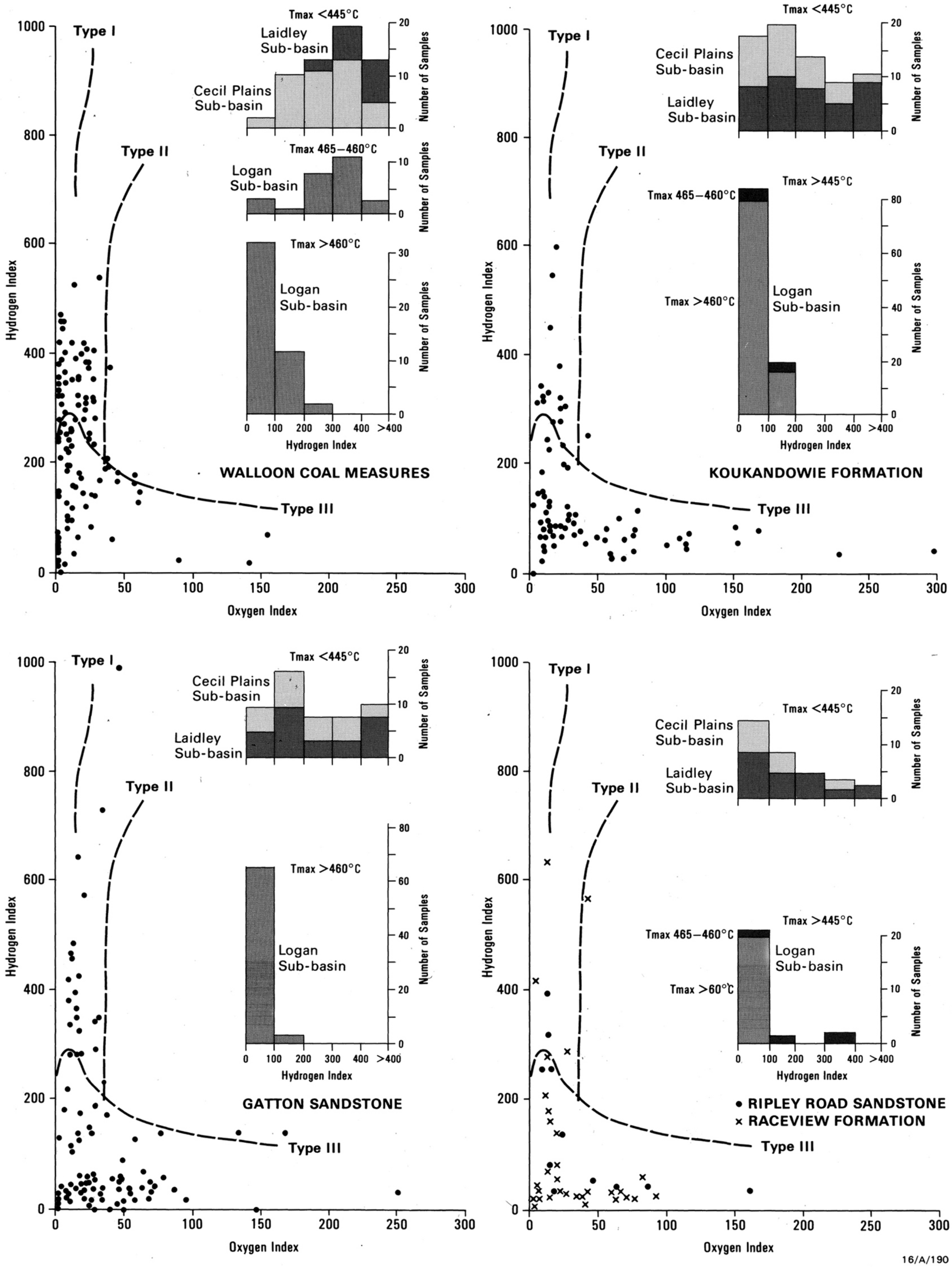


Figure 24. Classification of kerogen types based on hydrogen and oxygen indices according to Tmax and basin position, Clarence-Moreton Basin. (After Powell and others, 1993.)

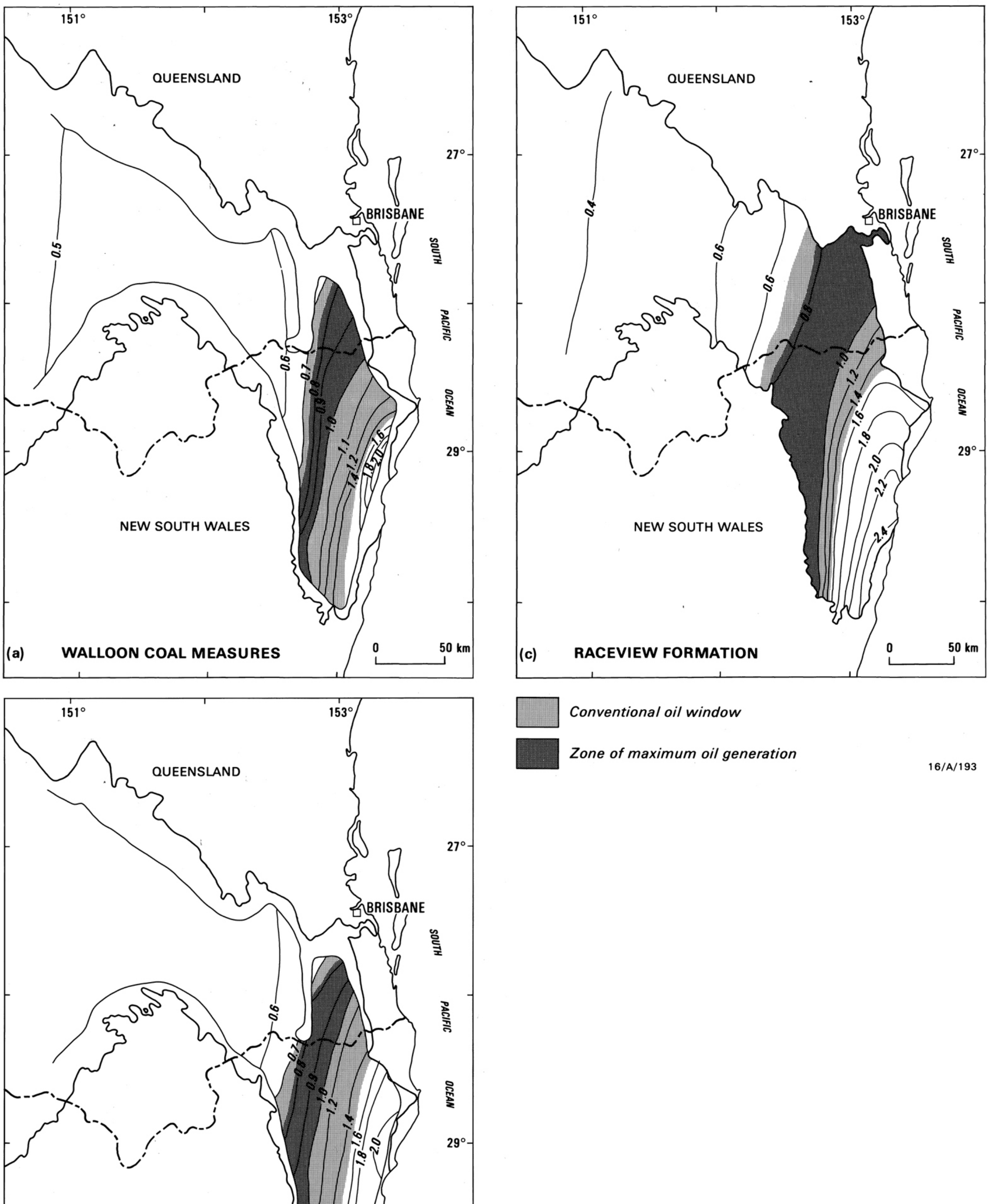


Figure 25. Regional maturation maps for the Clarence-Moreton Basin. Isoreflectance contours are derived from vitrinite reflectance and by conversion of Rock Eval data. (After Powell and others, 1993.)

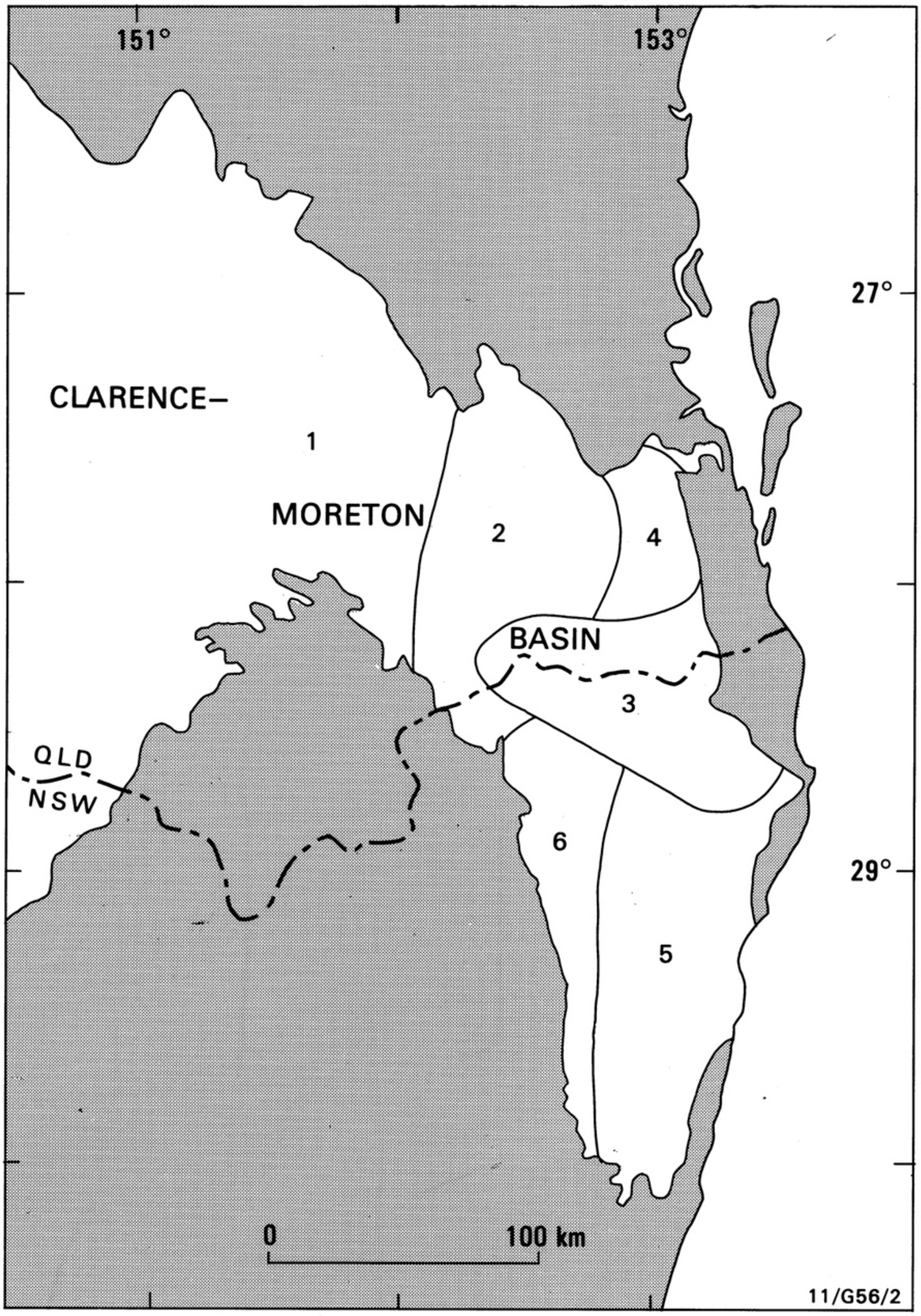


Figure 26. Areas of prospectivity in the Clarence-Moreton Basin, as defined by O'Brien and others (1994)

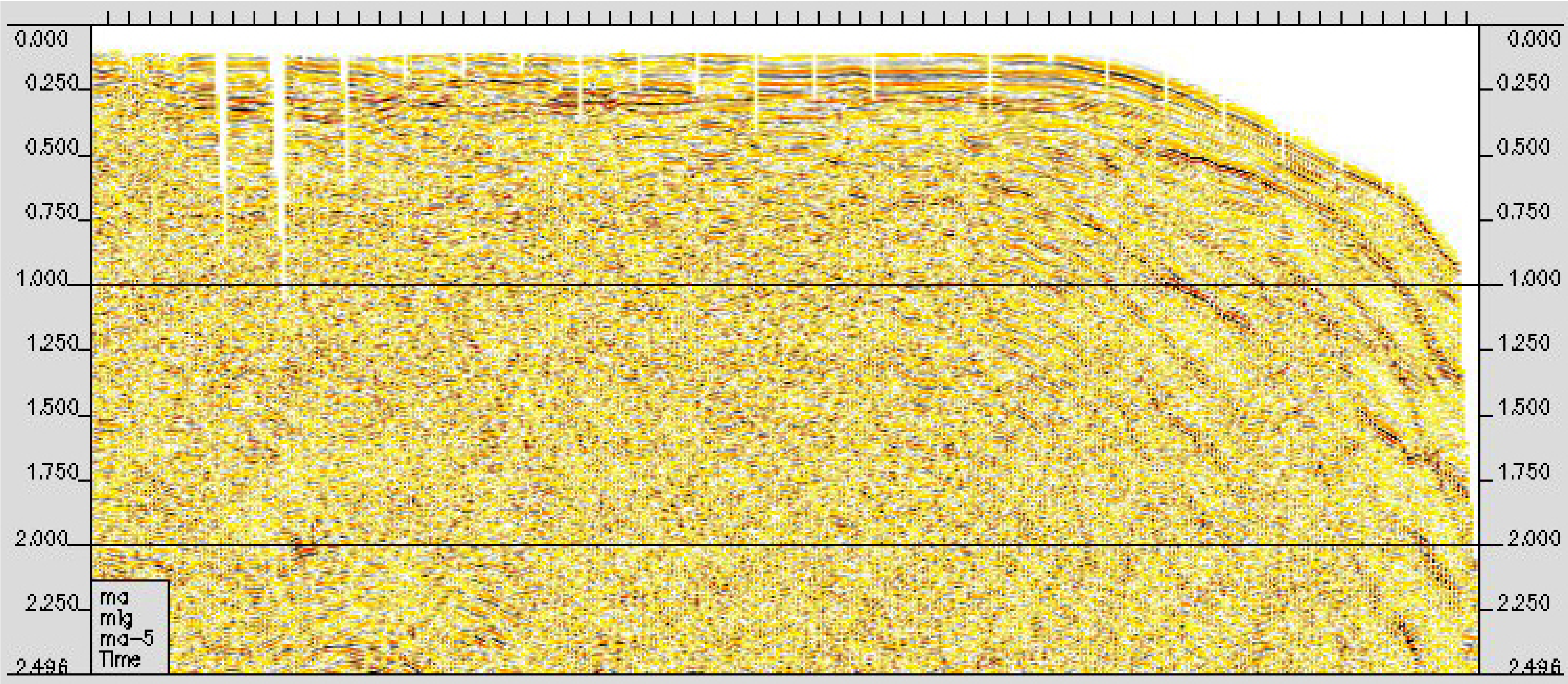


Figure 27. Portion of reprocessed seismic Line MA-05 from the Clarence River Seismic Survey. Data courtesy of the New South Wales Department of Mineral Resources

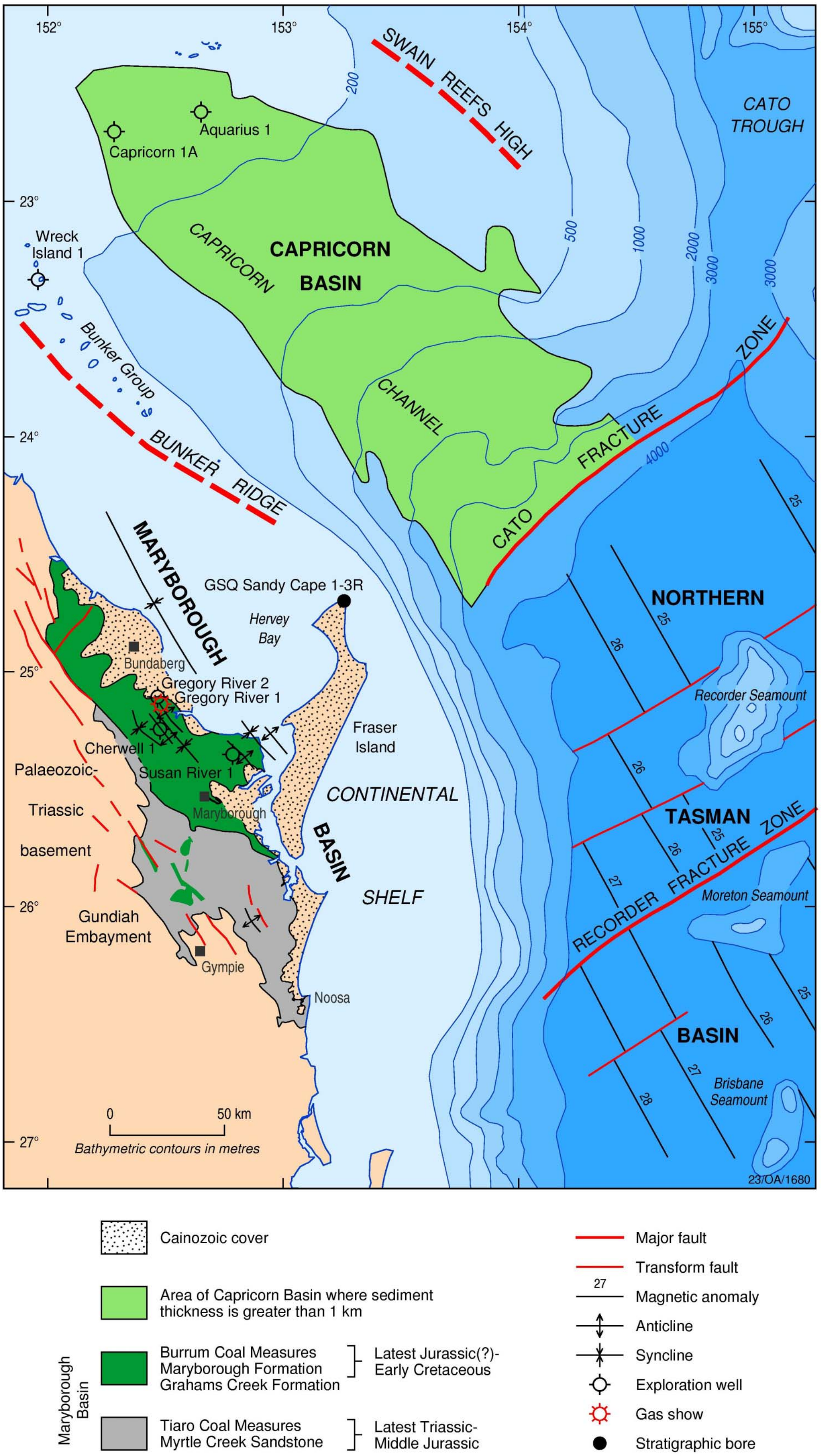


Figure 28. AGSO Survey 91 multichannel seismic reflection lines and sonobuoy experiment locations. (After Hill, 1994.)

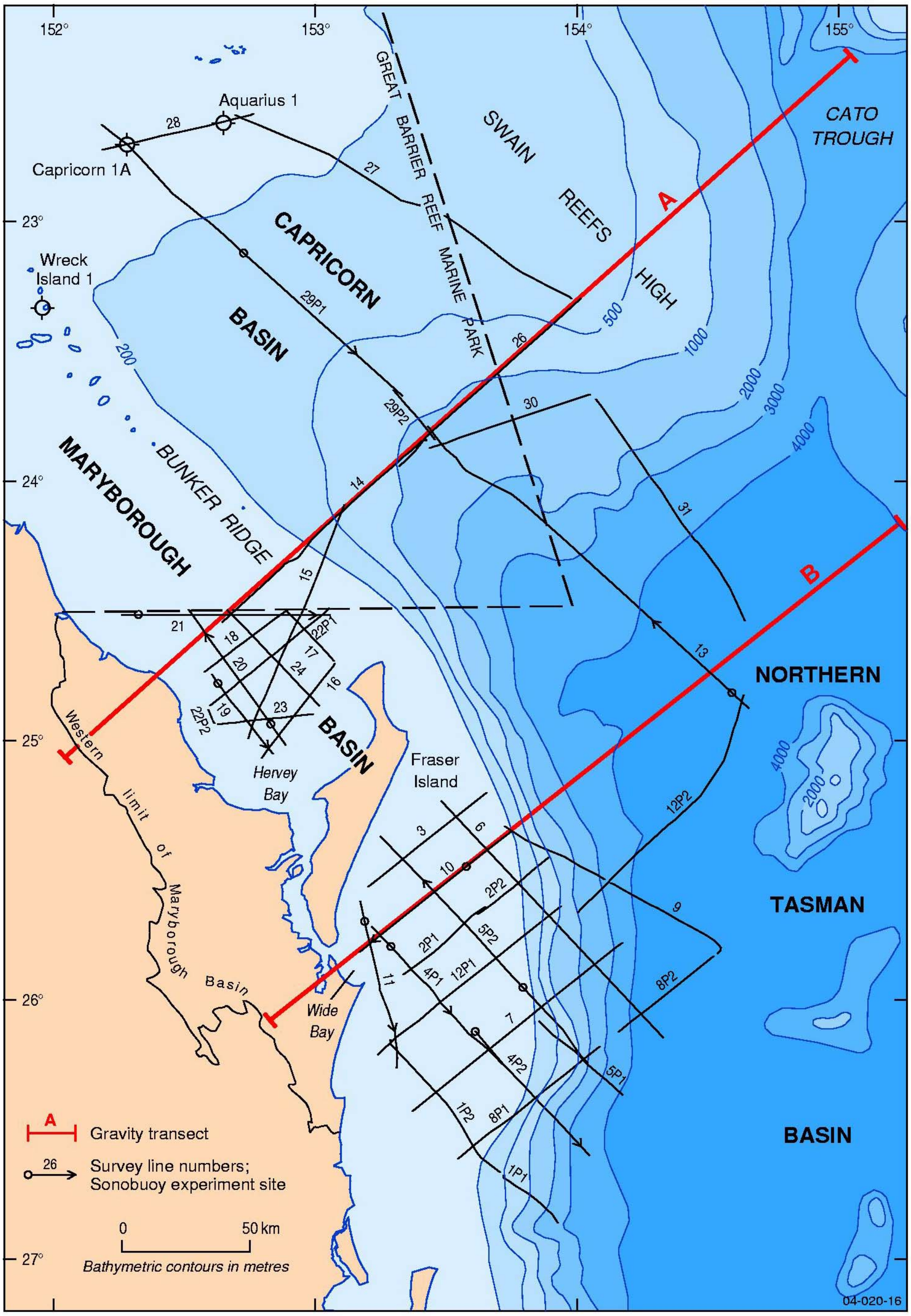


Figure 29. Portion of reprocessed seismic Line MA-05 from the Clarence River Seismic Survey. Data courtesy of the New South Wales Department of Mineral Resources

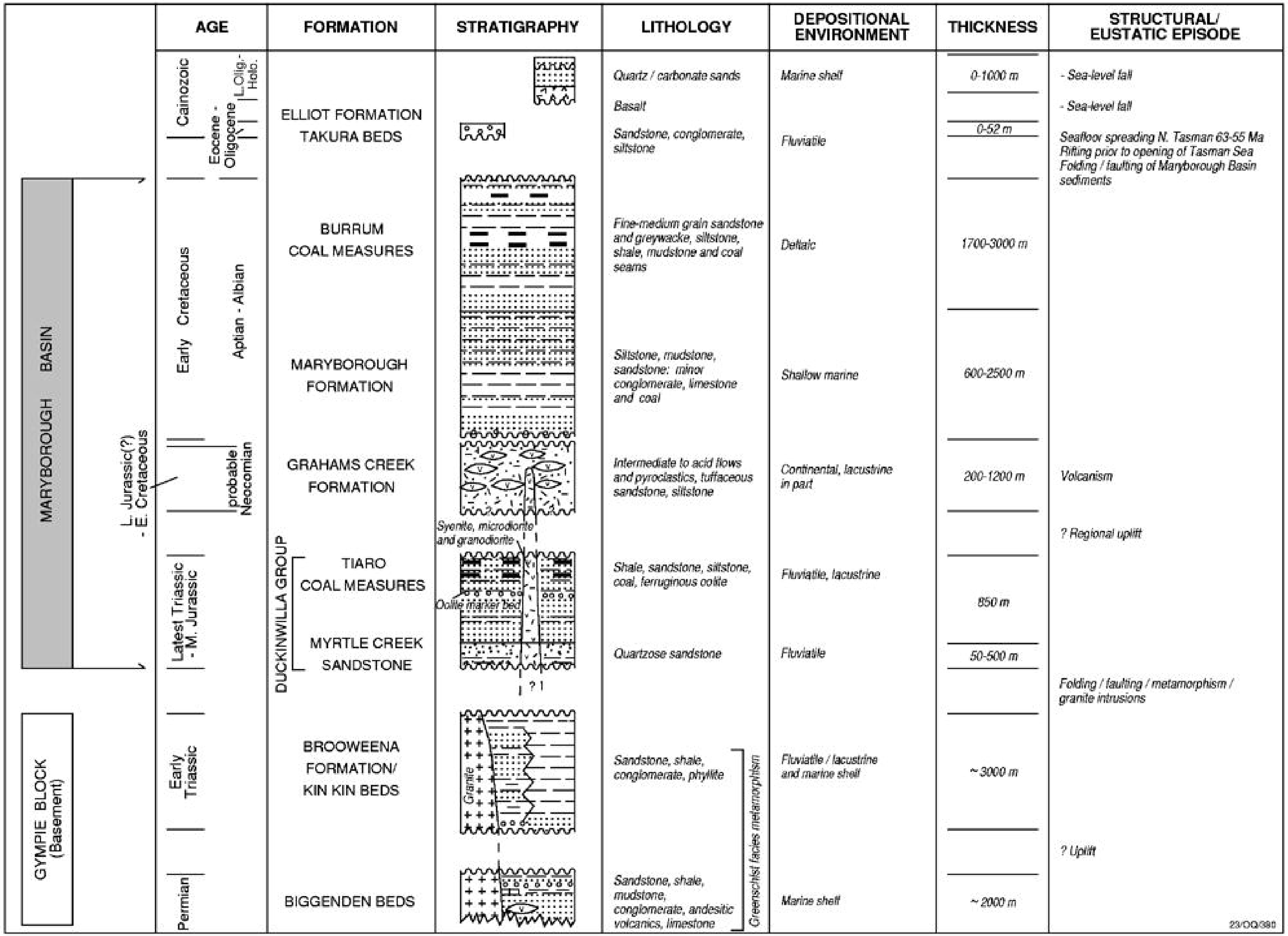


Figure 30. Lithostratigraphic relationships in the Maryborough Basin. (After Hill, 1994.)

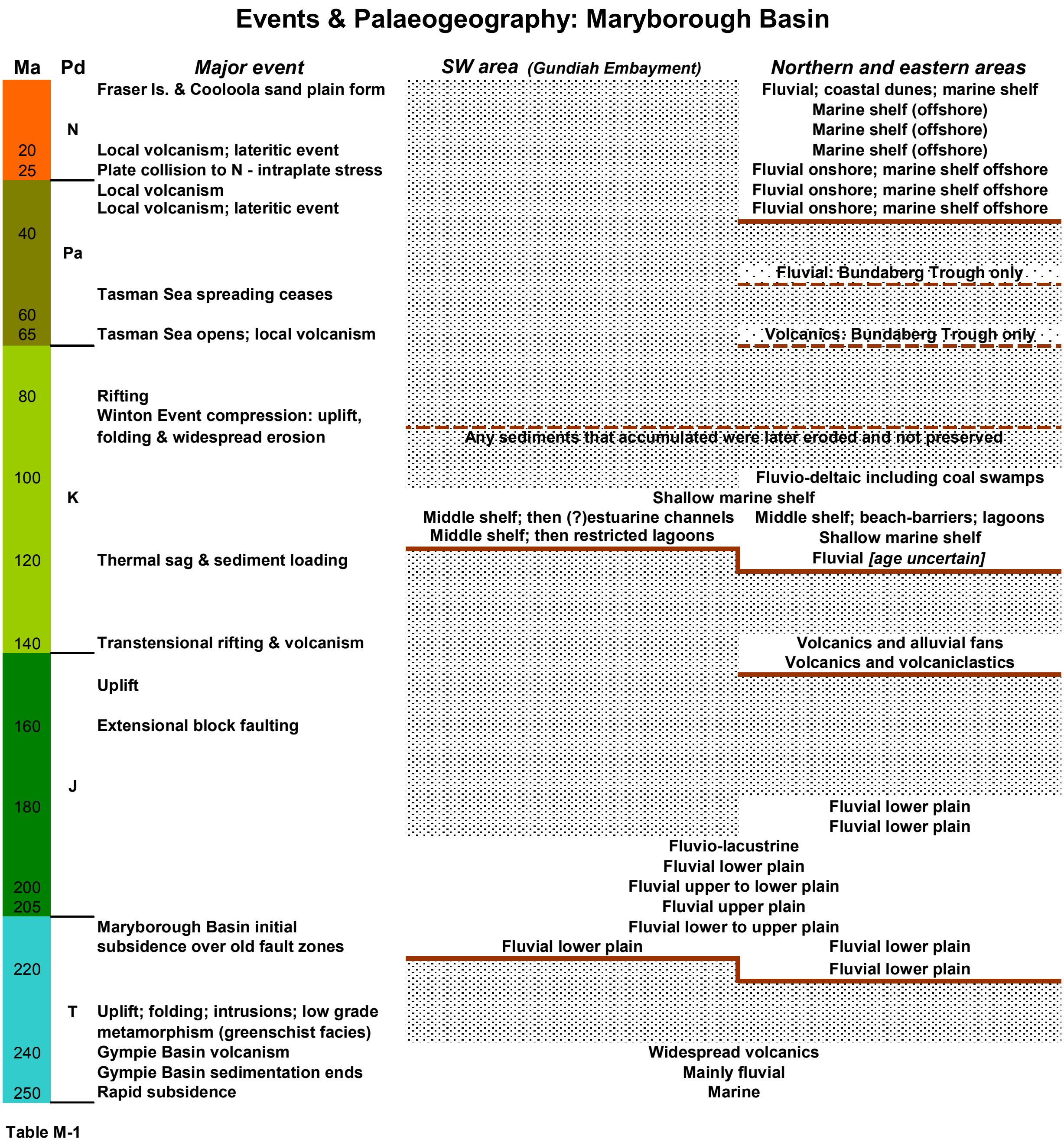


Figure 31. Major events and palaeogeography, Maryborough Basin

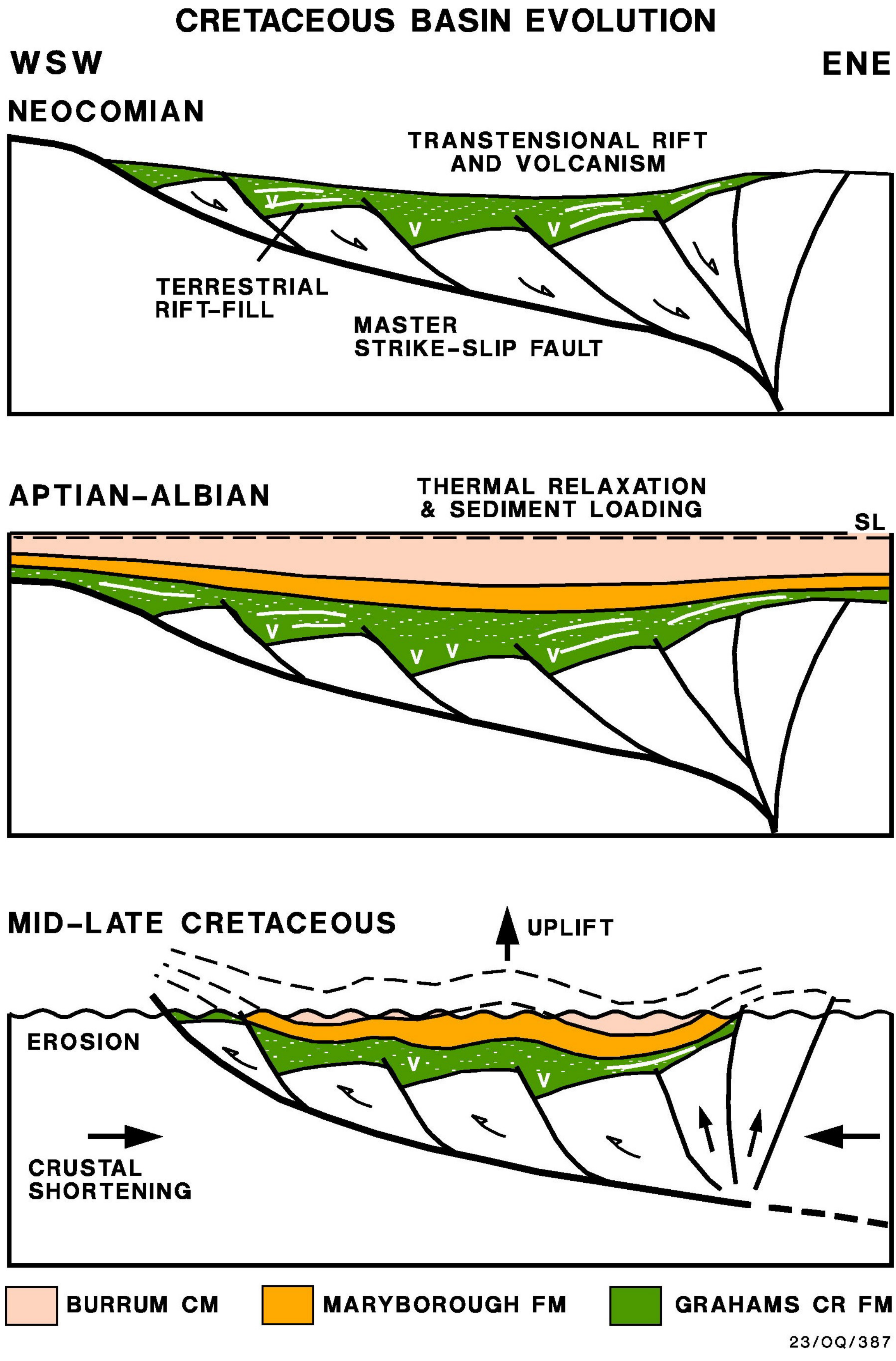


Figure 32. Hill's (1994) conceptual evolution of the Maryborough Basin during the Cretaceous

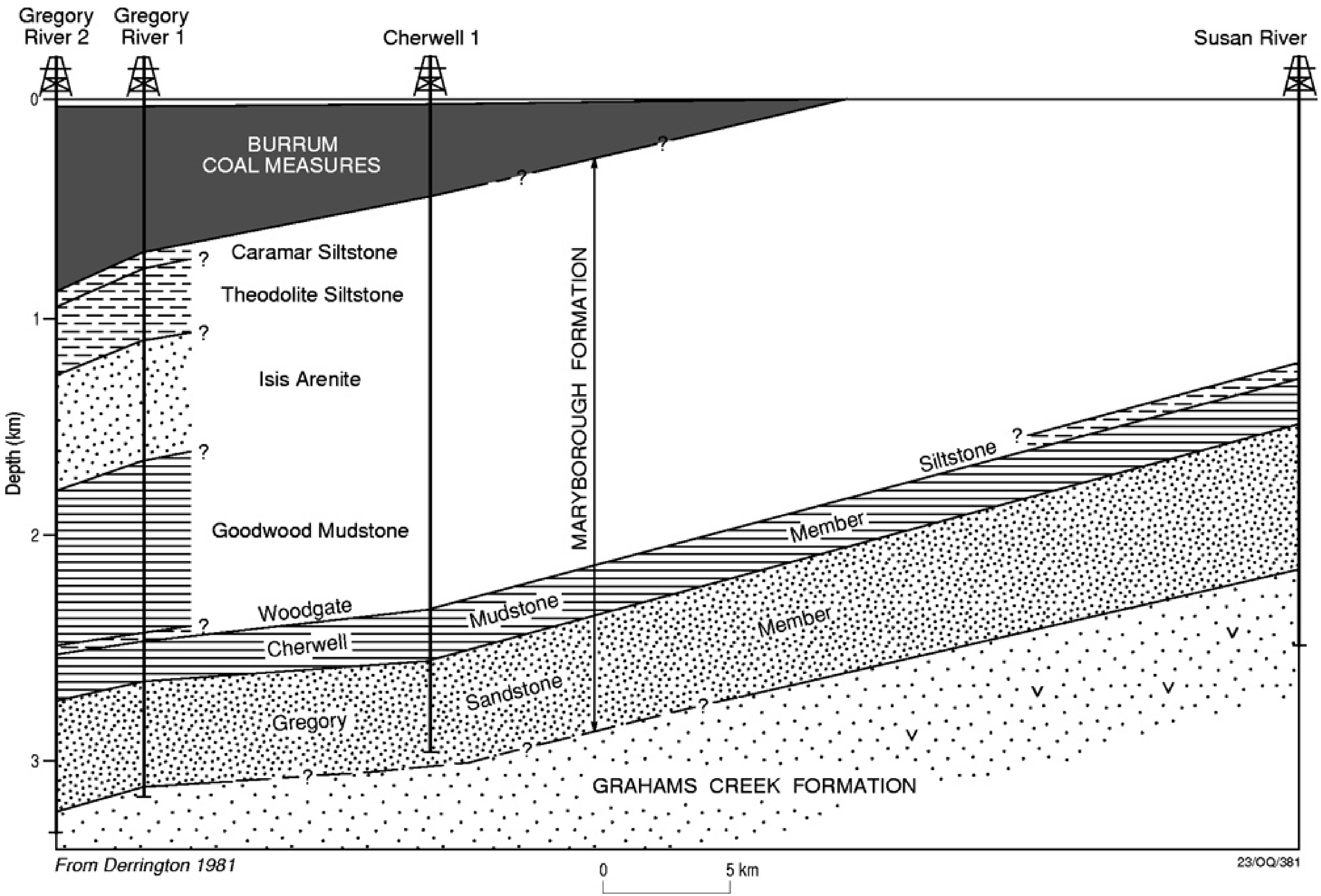


Figure 33. Stratigraphic correlation, Maryborough Basin wells. (After Derrington, 1981.)

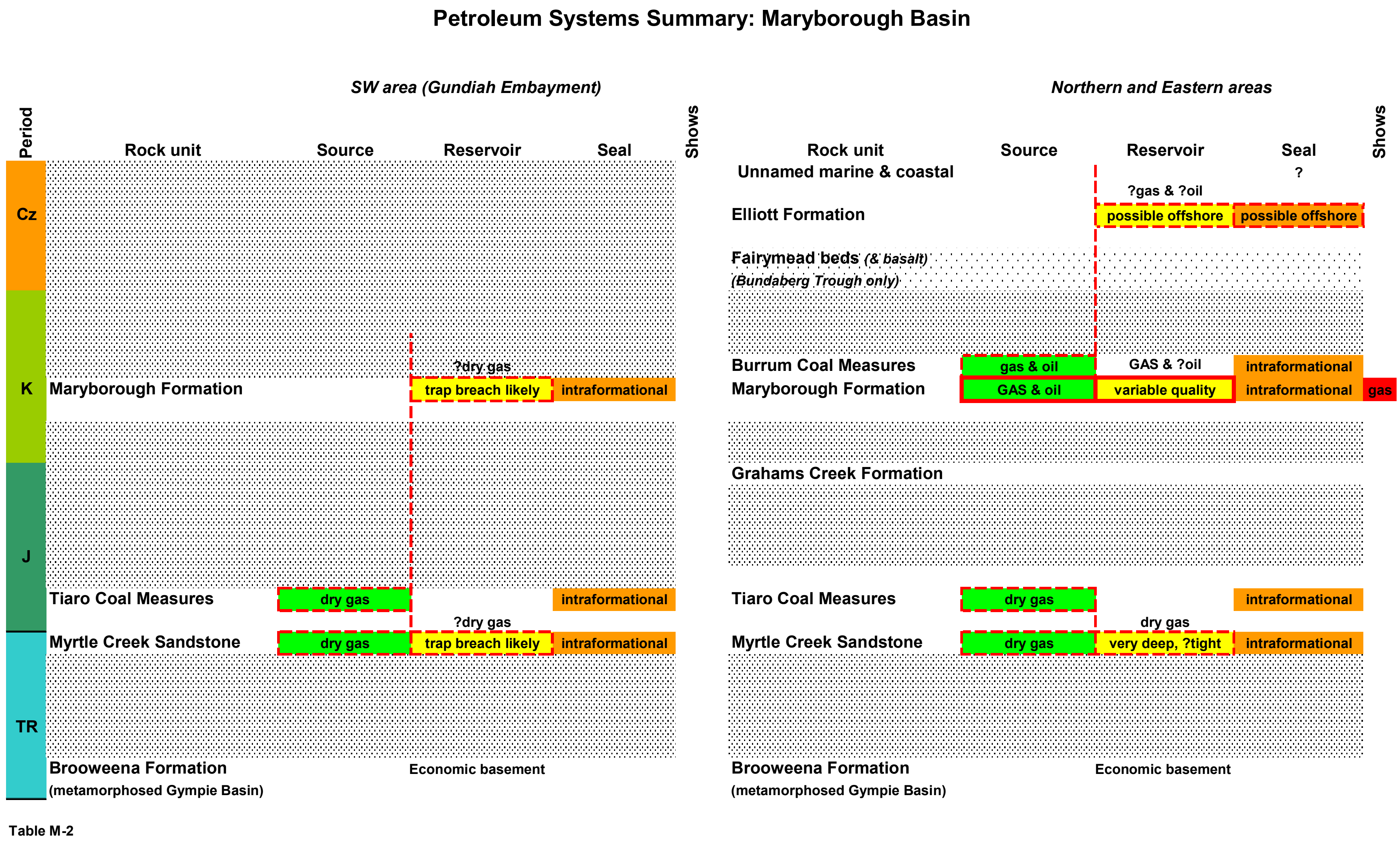


Figure 34. Petroleum systems summary, Maryborough Basin

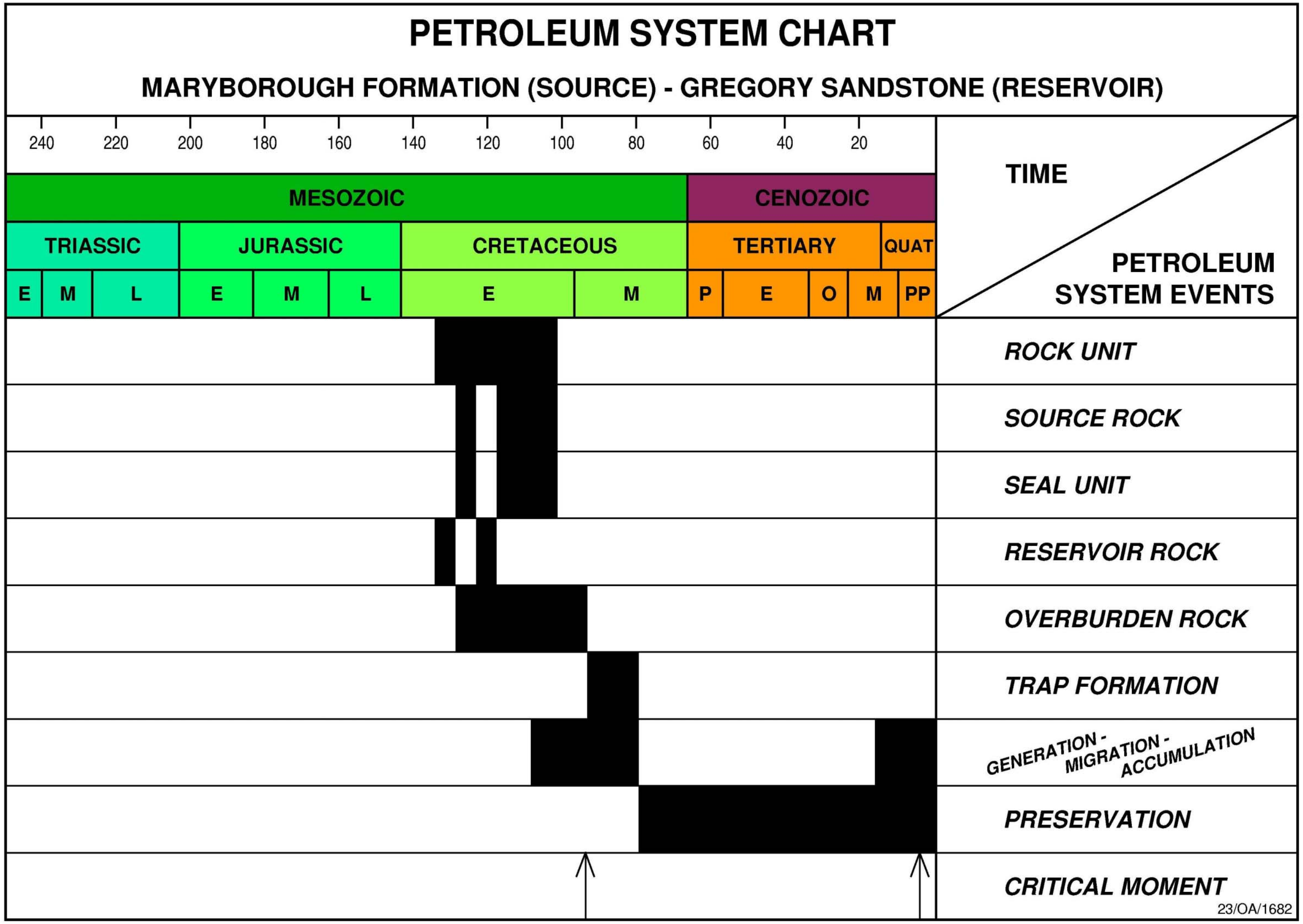


Figure 35. Maryborough Formation (source) - Gregory Sandstone Member (reservoir) petroleum systems chart, as viewed by Magellan Petroleum Australia Limited. (After Lipski, 2001.)

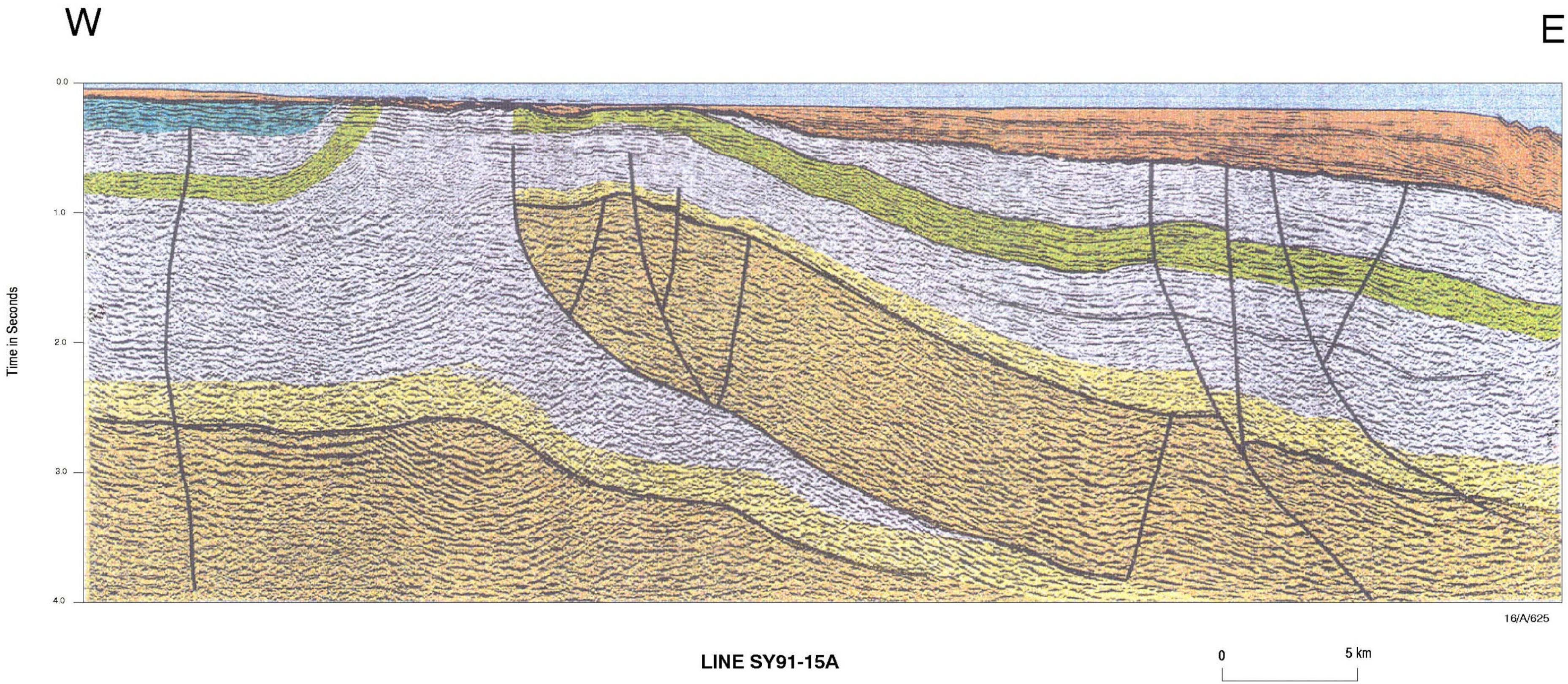


Figure 36. Sydney Basin seismic line SY9-15A, showing erosional truncation at the post-breakup unconformity level, across the shallowing eastern flank of the Offshore Uplift. (After Maung and others, 1997)

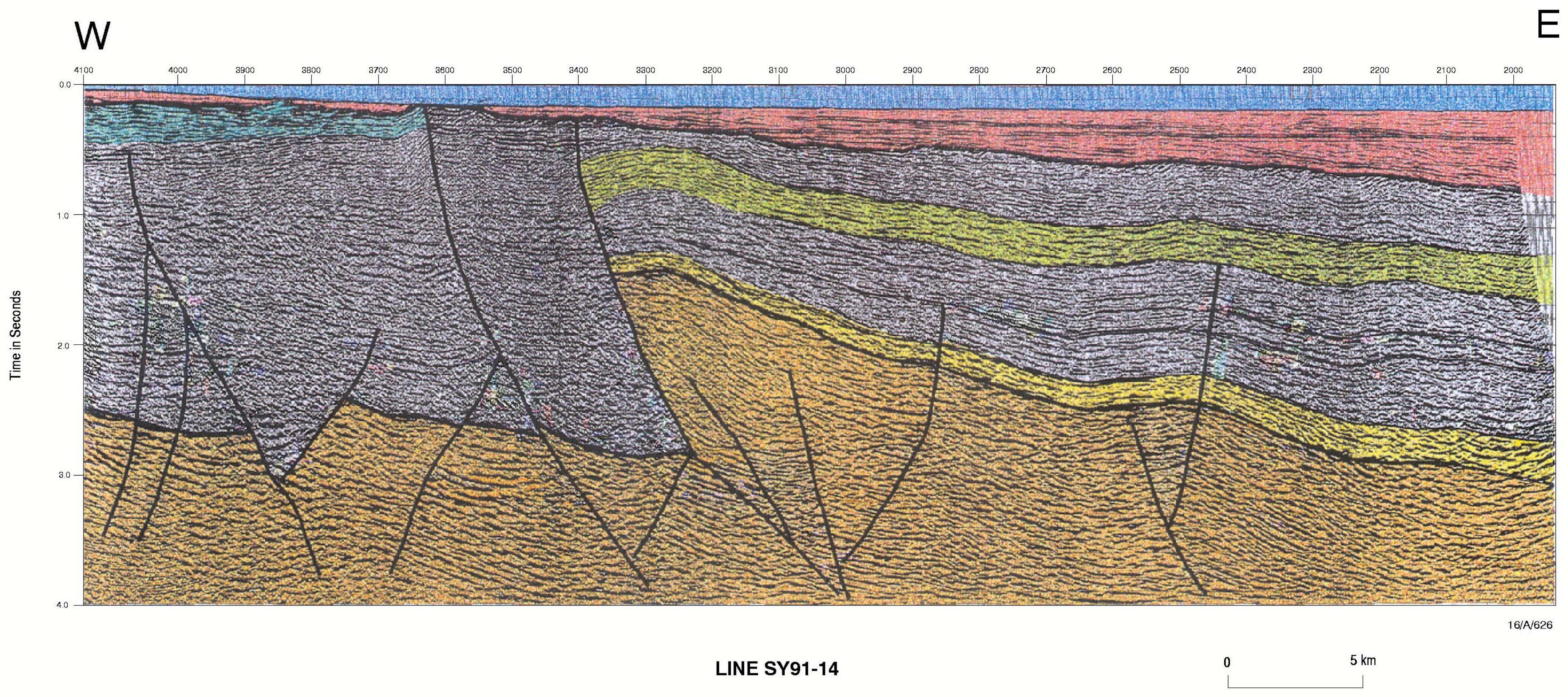


Figure 37. Sydney Basin seismic line SY91-14, showing the Offshore Uplift bound to the west by an interpreted low angle thrust complex. (After Maung and others, 1997)

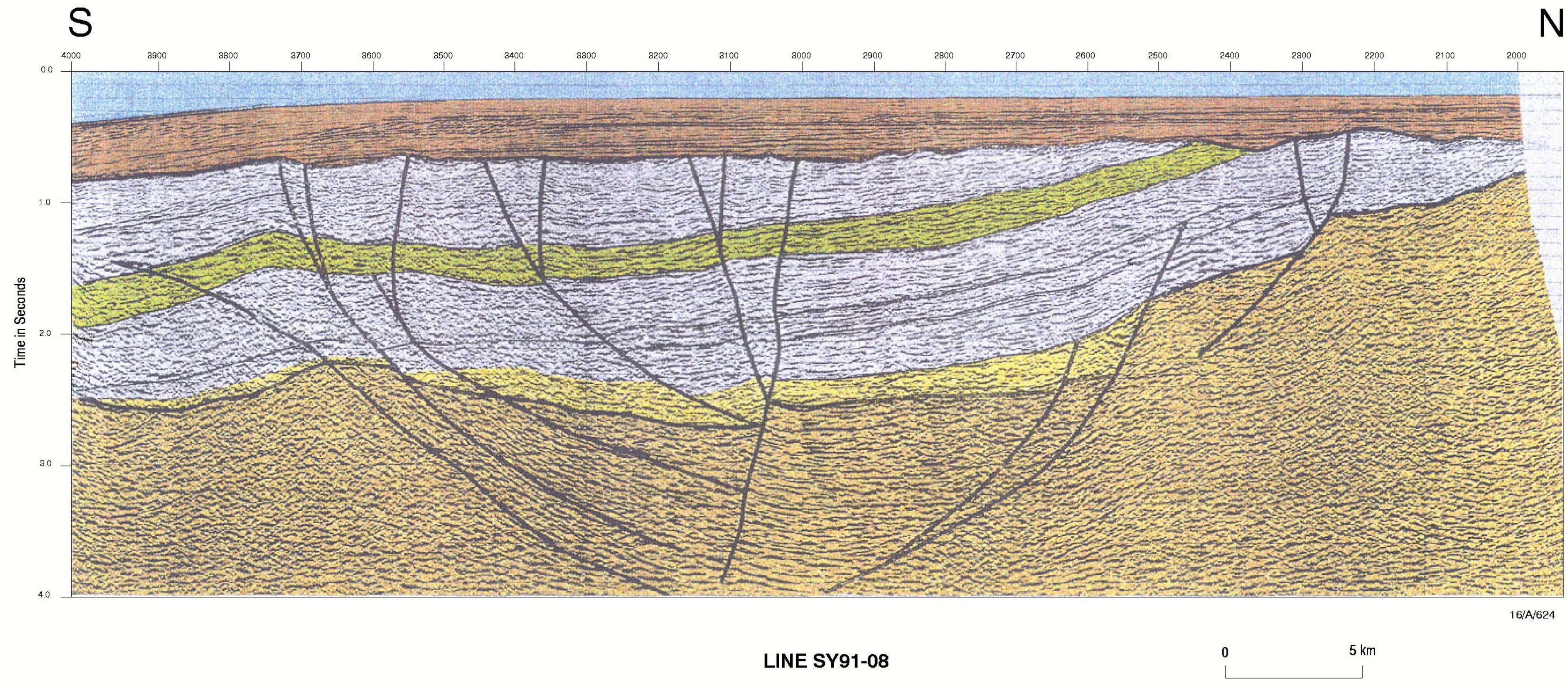


Figure 38. Sydney Basin seismic line SY91-08, showing the geometry of the Newcastle Syncline, the sediments of which were inferred by Maung and others (1997) to have been originally much more widespread. (After Maung and others, 1997)