Crude oil and potential source rock studies in the Eromanga Basin

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CRUDE OIL AND POTENTIAL SOURCE ROCK STUDIES
IN THE EROMANGA BASIN

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ABSTRACT

Hydrocarbon deposits occur at a number of stratigraphic levels within the Cooper/Eromanga Basin sequence in Australia. Sedimentary sequences contained in the Permo-Triassic Cooper Basin sequence are mainly fluvial and lacustrine in origin. Continental type sediments are predominant in the lower part (Jurassic) of the overlying Eromanga Basin sequence. The lower part of the Cretaceous is mainly shallow marine and grades up through a paralic sequence to a thick succession of fluvial origin. Organic petrological studies show that the Permian section in the Jackson/Naccowlah area has very good source potential and that the source potential is poor to fair in the Mesozoic section. In contrast, the Mesozoic section, particularly the lower part, has a very good source potential in the Merrimelia/Packsaddle area, where very little, or no, Permian section is preserved.

Crude oil geochemistry shows that there are two distinct groups (or families) of oils occurring in the study area, with characteristic different n-alkane distribution profiles and alkane parameters. Pristane to phytane ratios are consistently high, but variable, indicating the source material for the crude oils is predominantly phytoclasts derived from land plants. The presence of two distinct groups of crude oils is due to the differences in the maximum levels of thermal maturation attained by the source material possibly with some influence from organic matter type.
A good correlation exists between the microscopically determined volumetric abundance of organic matter and the amount of solvent extractable organic components. High pristane to phytane ratios in the extracts confirm the terrestrial origin of the source material contained in the units sampled. The n-alkane distribution profiles show a significant variation within the same stratigraphic unit; particularly in the marginally mature sequences. Correlation between the crude oils and source rock extracts using n-alkane distribution profiles is generally fair to good for the group I oils and the Jurassic extracts. A good match was not obtained between any of the source rock extracts and the waxy group II oils.
The research work for this thesis was carried out at the University of Wollongong, under the supervision of Professor A.C. Cook. Where the work of others whether published or unpublished, has been referred to, acknowledgement is given.
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CHAPTER 1

INTRODUCTION

The presence of hydrocarbon accumulations within the stratigraphic sequence in the Great Artesian Basin, of which the Eromanga Basin is a part, has been known since 1900 (Sprigg, 1982). Commercial quantities of gas were discovered in the underlying Permi-Triassic Cooper Basin sequence at Gidgealpa in 1963. The first major hydrocarbon discovery in the Jurassic Eromanga Basin sequence was made in 1976 when Namur-1 produced gas from the Upper Jurassic Namur Sandstone. Since then over fifty hydrocarbon discoveries have been made up to the end of 1983 within the Cooper/Eromanga Basin sequence from the stratigraphic horizons ranging from Early Permian to Early Cretaceous in age. Major hydrocarbon discoveries within the Cooper/Eromanga Basin sequence are summarized by Kantsler et al. (1983) and Armstrong and Barr (1982). The association of hydrocarbons in the Cooper/Eromanga Basins, with dominantly land plant derived organic matter is reported by several workers, e.g., Brooks (1970), Smyth (1979) and Kantsler et al. (1982). Cook (1982) has grouped the sedimentary sequence in the Mesozoic Eromanga Basin into four distinct organic facies based on the relative proportions of different macerals present in the organic matter assemblages.

Crude oils reservoired in the Cooper/Eromanga Basins are generally high paraffinic type with a variable wax content. McKirdy (1982) has divided the crude oils reservoired in the Mesozoic Eromanga Basin sequence into three main types; 'heavy', waxy paraffinic (37-41° API, 19-41°C pour point), e.g., Poolowanna-1 (Poolowanna Beds), Jackson
No.1 (Westbourne, Hutton); intermediate paraffinic-naphthenic (45-49° API, 8-12°C pour point) e.g., Strzelecki-3 (Birkhead, Hutton) and light, low wax paraffinic (49-57° API, 0°C pour point) e.g., Cuttapirrie-1 (basal Jurassic), Merrimelia-8, 10 (Namur, Hutton), Dullingari North-1 (Murta). All crude oils have a high pristane to phytane ratio indicating a higher land plant origin but the ratios span a large range of values.

Within the predominantly land plant derived organic matter rich sedimentary sequence in the Cooper/Eromanga Basins, several potential source rock horizons have been identified, based on the organic petrological and organic geochemical evidences, e.g., Thomas (1982), Schwebel et al. (1980), Cook (1982), and McKirdy (1982). Kantsler et al. (1983) concluded that fair to good and locally rich source rocks occur throughout the Permian section and, to a lesser extent, in the Jurassic sequence. Source potential is mainly due to the presence of a number of thin, rich source rock intervals, particularly within the Birkhead Formation but also at the base of Hutton Sandstone and within the Murta Member. McKirdy (1982) attributed the best source potential to the Jurassic Birkhead Formation and to the Murta Member while fair source potential was also detected in the Poolowanna Beds, basal Jurassic and Namur Sandstone Member.

The aim of this study is to solve the following problems:

(a) evaluate the chemical composition of the crude oils reservoired in the Eromanga Basin sequence in order to determine the compositional similarities and dissimilarities between different crude oils and, thus, the genetic relations between different crude oils within the basin;

(b) assess the composition of the organic matter by petrological method, of selected stratigraphic horizons from the
Cooper/Eromanga Basin sequence, in order to assess the relative source potential of the stratigraphic units based upon the organic matter content and the levels of organic maturity; 

(c) determine the chemical composition of the organic matter extracted from the potential source horizons, and the pyrolysis yield to determine the source potential by chemical methods (i.e., methods independent from those of organic petrology); 

(d) compare the source potentials obtained by organic petrological and organic geochemical methods to evaluate the compatibility of the methods used; and 

(e) compare the chemical composition of crude oils and the source rock extracts to examine any similarities as a clue to the genetic relationships between crude oils and potential source rocks.

To achieve this target four wells grouped in two pairs were selected. The two sets of pairs are located in two different parts of the basin. Members of each well pair are from the same anticlinal trend, but at the time of sampling one was a known hydrocarbon producer while the other was a dry well or a hydrocarbon show only. A fifth well was sampled to substantiate the information about the Permian section which is not well preserved in one well pair.

Subsequent to the completion of most of the experimental work the operator of the permits drilled a well near a previously "dry" structure that had already been assessed by the author as having significant source potential. These results had been communicated to the operator in the form of a seminar given on the progress of the study. This well appears to have discovered commercially viable oil-field, thus confirming the conclusions of the study at an inconveniently early stage.
4.

The concepts and philosophy behind this study are described in Chapter 3. Experimental methods and the results obtained are given in Chapters 4, 5 and 6. The extent of success obtained is summarized in Chapter 7, and the whole exercise is concluded in Chapter 8.
Geology of the project area

The five bore holes selected for this study are Jackson No.1, (Latitude, 27° 36′ 36"S, Longitude 142° 25′ 12"E), Naccowlah No.1, (Latitude, 27° 29′ 08.88"S, Longitude 142° 06′ 40.76"E), Merrimelia No.5, (Latitude 27° 46′ 30"S, Longitude 140° 09′ 20"E) Merrimelia No.8, (Latitude 27° 43′ 41.68"S, Longitude 140° 11′ 15.78"E) and Packsaddle No.3, (Latitude 27° 31′ 30.16"S, Longitude 140° 41′ 28.03"E) (Fig. 1). These boreholes lie within the Eromanga Basin (Early Jurassic to Late Cretaceous age) where it overlies the Cooper Basin, a sedimentary basin of Permo-Triassic age. They penetrate both the Eromanga Basin sequence and the underlying Cooper Basin sequence. However Merrimelia No.8 and Packsaddle No.3 are drilled on structures that are "bald" of the Permian sequence on their crests. Various aspects of the geology of parts of the Cooper Basin have been described by several authors since 1965 (e.g., Kapel, 1966, 1972; Canaple and Smith, 1965; Papalia 1969; Gatehouse, 1972) and a summary of work carried out up to 1975 is given in a paper by Battersby (1976). Recent developments in many aspects of the Cooper-Eromanga Basin studies are summarized by Moore and Mount (1982).

2.1 Geological Setting - Cooper Basin

The Cooper Basin is a NE-SW trending sedimentary basin located in the north-east corner of South Australia and the South-west corner of Queensland and covers an approximate area of 127,000 km² (Battersby, 1976; Fig 2). The sedimentary sequence within the Cooper Basin ranges from Early Permian to Middle Triassic in age and unconformably overlies a pre-Permian basement sequence composed of rocks that are
• a Merrimelia No. 8
  and
  Merrimelia No. 5
• b Packsaddle No. 3
• c Naccowlah No. 1
• d Jackson No. 1

Fig. 2.1 Location map of the bore holes selected for the study.
Fig. 2.2 Location map of the Cooper and Eromanga Basins.
upper Proterozoic to Lower Carboniferous age. The limits of Cooper Basin are defined by Kopperamanna-Warbreccan high to the west, a basement ridge of Proterozoic and Lower Palaeozoic rocks to the south, a subsurface platform of folded sediments of Proterozoic to Early Palaeozoic age to the east and the Canaway Ridge to the northeast (Fig. 3). Most of the structural elements contained within the Cooper Basin are semiarcuate trending roughly NE-SW, except for the east-west trending Arrabury-Karmona major anticlinal trend which subdivides the basin into two halves (Fig. 4). The northern half typically has a thick Triassic sequence and a thin Permian sequence. The majority of structures here are related to Tertiary movements. In the southern half a thick Permian sequence is predominant with a thin Triassic sequence which tends to be thicker in troughs. Rejuvenation of pre-Permian highs during the Permian seems to have a major control over the existing structures. Two prominent anticlinal trends, Gidgealpa-Merrimelia and the Nappacoongee-Murteree anticlinal trends in the southern half of the basin, have divided it into three major NE-SW trending troughs. Many other anticlines in the southern Cooper Basin are at least fault controlled and the majority of them are subparallel to the two main arcuate trends. Rejuvenation of pre-Permian faults along the flanks of many structures occurred contemporaneously with deposition. Some structural movement seems to have occurred during deposition of Triassic sediments. Approximately North-South orientated structural features are predominant in the northern half of the Cooper Basin. Battersby (1976) summarizes the major depositional and tectonic phases of Cooper-Eromanga basinal sequence as:

(a) deposition of marine Cambrian and Ordovician;
(b) major orogeny in Late Silurian to Early Devonian;
(c) deposition of red beds in Late Devonian to Early Carboniferous;
(d) folding, faulting and erosion of red beds;
Fig. 2.3 Tectonic framework of the Cooper Basin (After Battersby, 1976).
Fig. 2.4 Schematic cross sections through the northern and southern parts of the Cooper/Eromanga Basin sequence (After Battersby, 1976)
11.

(e) epeirogenic downwarping in Late Carboniferous to Early Permian;
(f) deposition of continental Permo-Triassic with contemporaneous faulting along major pre-Permian structural trends;
(g) uplift and erosion in Middle-Late Triassic;
(h) major epeirogenic downwarping of most of eastern Australia initiating the Great Artesian Basin in Early Jurassic time;
(i) continental Jurassic deposition;
(j) major transgression in Late Jurassic to Early Cretaceous;
(k) regression on Late Cretaceous; and
(l) regional folding and faulting in Tertiary.

2.2 **Stratigraphy of the Cooper Basin**

The sedimentary rock sequence contained in the Cooper Basin ranges from early Lower Permian to Middle Triassic in age and were deposited mostly in floodplain and lacustrine environments. The oldest Permian sequence, the Merrimelia Formation was defined by Martin (1967). The identification and definition of various stratigraphic units have been made by several authors, e.g., Kapel (1966, 1972), Papalia (1969). The generalized stratigraphy of the Cooper/ Eromanga Basin (Kantsler et al.) is given in Figures 2-5. The stratigraphy of the Cooper Basin is summarized in Table 1.

In the southern part, sedimentation was more or less continuous from Early Permian to Middle Triassic time except for a period of uplift and erosion which occurred in several places towards the end of early Permian time. Some Permian formations were not deposited over parts of many anticlinal trends. Similarly Triassic Nappamerri Formation was not deposited over many areas including the Murteree structure. The thickest sediment pile is believed to occur in the Nappamerri Trough, where at least 1372m of Permian and 1762m of Triassic sediments probably occur.
<table>
<thead>
<tr>
<th>Name</th>
<th>First Formal Use</th>
<th>Type Section or area</th>
<th>Thickness</th>
<th>Relationships</th>
<th>Lithology</th>
<th>Fossils</th>
<th>Age</th>
<th>Environment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nappamerri</td>
<td>Gatehouse (1972)</td>
<td></td>
<td>Up to 2000' in northern Cooper Basin. Up to 2500' predicted for the Nappamerri Trough on the basis of seismic data</td>
<td>Unconformably overlain by Jurassic sediments</td>
<td>Varicoloured, sideritic and colomitic shales and siltstones with grey to brown kaolinitic, very fine grained to pebbly sandstone</td>
<td>Early to Middle Triassic</td>
<td>Lacustrine and continental fluviatile</td>
<td></td>
</tr>
<tr>
<td>Formation</td>
<td>Evans (1966)</td>
<td></td>
<td></td>
<td></td>
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<td></td>
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<td></td>
</tr>
<tr>
<td>Toolachee</td>
<td>Kapel (1972)</td>
<td>Toolachee No.1</td>
<td>Over 150m in Brumby No.1</td>
<td>Places conformably overlain by Nappamerri Fm elsewhere unconformably overlain by Jurassic sediments</td>
<td>Upper Unit (Unit A), carbonaceous shale with interbedded coal and sandstones, Lower Unit (Unit B) Coarse to fine grained sandstones with interbedded shales and coals</td>
<td>Upper Permian (Upper Stage 5)</td>
<td>Fluvial Floodplain</td>
<td></td>
</tr>
<tr>
<td>Formation</td>
<td>Gatehouse (1972)</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Daralingie Beds</td>
<td>Gatehouse (1972)</td>
<td>Daralingie No.1</td>
<td>Generally less than 30m, Thickest sections in the Tenapperra and Nappamerri Troughs, e.g., 294' in Burley No.1 hole</td>
<td>Places transitional into Toolachee Formation</td>
<td>Shale and siltstone with thin interbeds of sandstone and coal</td>
<td>Lower Permian (Lower Stage 5)</td>
<td>Lower deltaic to floodplain</td>
<td></td>
</tr>
<tr>
<td>Roseneath Shale</td>
<td>Gatehouse (1972)</td>
<td>Roseneath No.1</td>
<td>Thick sequence occur in Tenapperra Trough, e.g., 87m in Toolachee East No.1 well</td>
<td>Conformably overlaying Epsilon Formation</td>
<td>Dark grey to black carbonaceous shale and siltstone</td>
<td>Lower Stage 5</td>
<td>Lacustrine</td>
<td></td>
</tr>
</tbody>
</table>

Table 2.1 Stratigraphy of the Cooper Basin Sequence
<table>
<thead>
<tr>
<th>Name</th>
<th>First Formal Use</th>
<th>Type Section or area</th>
<th>Thickness</th>
<th>Relationships</th>
<th>Lithology</th>
<th>Fossils</th>
<th>Age</th>
<th>Environment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Epsilon Gatehouse (1972)</td>
<td>Epsilon No.4</td>
<td>Thickest in Tenappera and Nappanerri Troughs, e.g., 457' in Burley No.1. Average is about 200' and thins towards the basin margin</td>
<td>Conformably overlying the Murteree shale</td>
<td>Shale and siltstone with thinly interbedded sandstone and coal</td>
<td>Lower Stage 5 to Upper Stage 4</td>
<td>Lacustrine to floodplain</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Murteree Shale Gatehouse (1972)</td>
<td>Murteree No.1</td>
<td>Generally between 100'-200', thickest in Nappanerri and Tenapperi Troughs e.g., 263' in Burley No.1</td>
<td>Unconformable over Patchawarra Formation?</td>
<td>Dark grey to black carbonaceous and slightly micaceous shales and siltstones</td>
<td>Upper Stage 4 sub-division</td>
<td>Lacustrine</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Patchawarra Formation Kapel (1972)</td>
<td>Moorari No.1</td>
<td>Thickest sections in Patchawarra Trough, e.g., 1574' in Tindilpie No.1 and in the Nappaneri Trough, e.g., 1936' in Innamincka No.2, Ranges from 400'-1600'.</td>
<td>Upper unit is transitional to Murteree Shale</td>
<td>Sandstones, shales, coals, siltstones and minor conglomerates in the upper part, Carbonaceous shale with thinly interbedded coals and minor sandstones</td>
<td>Stage 3 to Upper Stage 4</td>
<td>Deltaic to floodplain</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tirrawarra Formation Kapel (1972)</td>
<td>Tirrawarra No.1</td>
<td>Generally between 50' to 250'</td>
<td>Disconformably overlie the Merrimelia Formation</td>
<td>Brown and white sandstone, fine to medium grained, subrounded, moderately well sorted</td>
<td>Stage 2</td>
<td>Fluviatile i.e., Late Carboniferous to Early Permian</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Merrimelia Formation Grund (1966)</td>
<td></td>
<td>Thickest in the Nappaneri Trough, eg, 1350' plus, in Tallalia No.1</td>
<td>Sandstone, conglomerates, conglomeratic shales, siltstones and shales (glacial, glacio-fluvial, periglacial, glacio-lacustrine, and interglacial sediments)</td>
<td>Stage 2</td>
<td>Glacial i.e., Late Glacio-Carbonifer-Lacustrine to Glacio-Early Fluvial Permian</td>
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</tbody>
</table>
Fig. 2.5 Generalized stratigraphy of the Cooper/Eromanga Basin sequence (After Kantsler et al., 1983).
2.3 The Eromanga Basin

The Mesozoic Eromanga Basin sequence in the project area ranges from Early Jurassic to Late Cretaceous in age. The geology of the Eromanga Basin has been described by several authors (e.g., Senior et al., 1968; Exon and Senior, 1976; Senior et al., 1978; and Senior and Habermehl, 1980). The Eromanga Basin covers an area of about 1,000,000 km² and below it are four older sedimentary basins: the Adavale Basin (Middle Devonian to Lower Carboniferous) and Cooper Basin (Lower Permian to Middle Triassic) are entirely concealed, but the Drummond (Upper Devonian to Lower Carboniferous) and Galilee (Upper Carboniferous to Upper Triassic) Basins are only partly concealed.

The Jurassic sedimentary sequence in the Eromanga Basin is mainly terrestrial comprising quartzose arenite interbedded with carbonaceous siltstones and mudstones and minor coal. The thickness of the Jurassic sequence varies from 500 to 1200 meters. The preserved Cretaceous sequence is 500 to 1800 meters thick in the central Eromanga Basin area. The Early Cretaceous sequence is shallow marine, consists of tabular arenites, interbedded with montmorillonite-rich siltstones, mudstones and claystones. The lithology of the Late Cretaceous sequence is similar, but was deposited in paralic, lacustrine and fluvial environments. The whole area is covered sporadically by Late Tertiary and more generally by unconsolidated Quarternary sediments. The stratigraphy of the Eromanga Basin sequence is summarized in Table 2 (After Senior et al., 1978).

Structurally the Eromanga Basin sequence is characterised by broad, low amplitude folds and linear faults with throws of up to 300m (Fig 2-3). Senior et al., (1978) concluded that most of the folds originated as drapes over basement blocks and horsts have a variety of trends; but most are northerly. Dips on their flanks are commonly 1°-2° at surface, increasing gradually with depth.
<table>
<thead>
<tr>
<th>Name</th>
<th>Derivation</th>
<th>Thickness</th>
<th>Lithology</th>
<th>Age</th>
</tr>
</thead>
<tbody>
<tr>
<td>WINTON FORMATION</td>
<td>Whitehouse, 1954</td>
<td>Top eroded, no complete sequence known. Up to 1200m thick in part of</td>
<td>Very labile sandstone, siltstone and mudstone, minor mudclast</td>
<td>Lower to Upper Cretaceous</td>
</tr>
<tr>
<td></td>
<td>Dunstan, 1916</td>
<td>Cooper Syncline and Thomson Syncline</td>
<td>conglomerate and coal: all calcareous, carbonaceous, pyritic in part. In</td>
<td>(Albian-Cenomanian)</td>
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<td></td>
<td></td>
<td></td>
<td>outcrop only calcareous rubble and concretions. Extensive chemical</td>
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<td></td>
<td></td>
<td></td>
<td>weathering profile consisting of kaolinised, silicified, and ferruginised</td>
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<td></td>
<td></td>
<td></td>
<td>rocks.</td>
<td></td>
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<tr>
<td>MACKUNDA FORMATION</td>
<td>Vine &amp; Day, 1965</td>
<td>Averages 60m. Up to 150m east of Canaway Fault in Powell Depression, and</td>
<td>Very labile to labile sandstone, siltstone and mudstone, calcareous in</td>
<td>Lower Cretaceous (Upper Albian)</td>
</tr>
<tr>
<td>Name</td>
<td>Derivation</td>
<td>Thickness</td>
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<tr>
<td>ALLARU MUDSTONE</td>
<td>Vine et al., 1967</td>
<td>270m in outcrop, maintained in subsurface; thins southward to Eulo Ridge</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Allaru Member</td>
<td>Vine &amp; Day, 1965</td>
<td></td>
<td></td>
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<tr>
<td>Wilgynya Formation</td>
<td>Casey, 1959</td>
<td></td>
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<tr>
<td>TOOLEBUC FORMATION</td>
<td>Senior et al., 1975</td>
<td>3-75m</td>
<td></td>
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<tr>
<td>Toolebuc Limestone</td>
<td>Vine et al., 1967</td>
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<tr>
<td>Toolebuc Member</td>
<td>Casey, 1959</td>
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<tr>
<td>COREENA MEMBER of Wallumbilla</td>
<td>Vine, 1966</td>
<td>25m in NE, thickening SW to 120m in central part of Eromanga Basin. Uniform at about 180m in Cunnamulla Shelf area</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Formation</td>
<td>Vine et al., 1967</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Lithology</td>
<td>Age</td>
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<tr>
<td>Blue-grey mudstone with interbeds of indurated calcareous siltstone and fine-grained very labile sandstone, and concretions. Mudstone very thinly bedded. Where weathered is kaolinitic, white to pale pink or grey, and siliceous</td>
<td>Lower Cretaceous (Upper Albian)</td>
<td></td>
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<tr>
<td>Fine-grained pale grey limestone; generally crops out as flat ovoid concretions averaging 15 cm across. Thin interbeds of grey to black calcareous labile sandstone and siltstone</td>
<td>Lower Cretaceous (Upper Albian)</td>
<td></td>
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</tr>
<tr>
<td>Coarse-grained siltstone to fine-grained very labile sandstone, interbedded with mudstone. Calcareous. Glauconite and fragments of andesite and plagioclase</td>
<td>Lower Cretaceous (lower to middle Albian)</td>
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<tr>
<td>Name</td>
<td>Derivation</td>
<td>Thickness</td>
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<tr>
<td>DONCASTER MEMBER of Wallumbilla Formation</td>
<td>Vine &amp; Day, 1965</td>
<td>150m in NE, gradually thickening SW to 220m in north-centre of map area and then thinning W towards Boulia Shelf; about 120m at NW corner of map area. SE about 240m thick over Cunnamulla Shelf and about 130m thick elsewhere</td>
<td>In outcrop, dark blue-grey mudstone with fine-grained glauconitic labile sandstone and siltstone. Gypsum common. Partly calcareous. Mudstone, thinly laminated, laminated and massive</td>
<td>Lower Cretaceous Cretaceous (Albian)</td>
</tr>
<tr>
<td>WYANDRA SANDSTONE MEMBER</td>
<td>Senior et al., 1975</td>
<td>3-18m varying slowly over considerable distances. Does not crop out in map area</td>
<td>Medium to coarse quartzose to sub-labile sandstone with scattered pebbles and carbonate cement. Porous and permeable; youngest pressure aquifer in the Eromanga Basin</td>
<td>Lower Cretaceous (upper Neocomian or lower Aptian)</td>
</tr>
<tr>
<td>CADNA-OWIE FORMATION (previous informal name &quot;Upper Hooray Sandstone&quot;)</td>
<td>Wopfner et al., 1970</td>
<td>15-75m. Does not crop out in map area</td>
<td>Fine to medium quartzose sandstone and very fine labile sandstone and siltstone, minor glauconite</td>
<td>Lower Cretaceous (Neocomian to lower Aptian)</td>
</tr>
<tr>
<td>HOORAY SANDSTONE</td>
<td>Hill &amp; Denmead, 1960, p.311; Exon, 1966</td>
<td>45-120m in outcrop and generally subsurface. As much as 400m in Nebine Ridge Cunnamulla Shelf area</td>
<td>Interbedded porous quartzose sandstone and siltstone</td>
<td>Upper Jurassic to Lower Cretaceous (Neocomian to Albian)</td>
</tr>
<tr>
<td>INJUNE CREEK GROUP Injune Creek Beds</td>
<td>Exon, 1966 Jensen, 1921, p.92</td>
<td>200m, thins NW and absent from Thargomindah and Cunnamulla Shelves</td>
<td>Siltstone, mudstone and sandstone; coal</td>
<td>Middle to Upper Jurassic</td>
</tr>
<tr>
<td>Name</td>
<td>Derivation</td>
<td>Thickness</td>
<td>Lithology</td>
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<td></td>
</tr>
<tr>
<td>WESTBOURNE FORMATION</td>
<td>Gerrard, 1964; Exon, 1966</td>
<td>120m near Tambo, thins to 60m about 50km to N. Subsurface about 100m. Thins southward and wedges out against Thargomindah and Cunnamulla Shelves</td>
<td>Siltstone, mudstone, fine-grained quartzose sandstone</td>
<td></td>
</tr>
<tr>
<td>ADORI SANDSTONE</td>
<td>Woolley, 1941; Hill &amp; Denmean, 1960; Exon, 1966</td>
<td>Maximum 71m in outcrop. 26-70m subsurface</td>
<td>White fine to medium clayey sublabile to labile sandstone, minor pebbles and coarse sandstone, minor siltstone and mudstone. Sandstone cross-bedded and medium to thick-bedded, friable and porous in part.</td>
<td></td>
</tr>
<tr>
<td>BIRKHEAD FORMATION</td>
<td>Exon, 1966</td>
<td>Outcrop about 90m, subsurface about 110m. Absent from NE, S, and SE of map area</td>
<td>Outcrop: fine calcareous sandstone and siltstone. Subsurface: fine buff, grey, or green sublabile and labile sandstone, in part calcareous, grey siltstone, carbonaceous mudstone, and minor coal</td>
<td></td>
</tr>
<tr>
<td>Name</td>
<td>Derivation</td>
<td>Thickness</td>
<td>Lithology</td>
<td>Age</td>
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</tr>
<tr>
<td>HUTTON SANDSTONE</td>
<td>Reeves, 1947; Mollan et al., 1970</td>
<td>120-150m in outcrop, up to 250m in subcrop. Thin or absent on Thargomindah</td>
<td>Outcrop: quartzose sandstone with abundant siltstone and mudstone in upper part. Fine conglomerate beds and scattered quartz pebbles in sandstone. Bedding thick and poor, with some planar and scour cross beds. Siltstone and mudstone commonly carbonaceous—generally laminated to thinly bedded. Local claystone in upper part</td>
<td>Lower to Middle Jurassic</td>
</tr>
<tr>
<td>EVERGREEN BOXVALE SANDSTONE MEMBER</td>
<td>Whitehouse, 1952, Bundamba Group 1954</td>
<td>11-40m; probably thickens. Thins NW from about 75m at edge of map area to about 45m near Birkhead Anticline</td>
<td>Siltstone, mudstone, subordinate Quartzose sandstone and siltstone. Can be divided into lower arenaceous and upper arenaceous and argillaceous sequences</td>
<td>Lower Jurassic</td>
</tr>
<tr>
<td>PRECIPICE SANDSTONE</td>
<td>Whitehouse, 1954; Mollan et al., 1970</td>
<td>Approx. 45m over Birkhead Anticline. Probably reaches 100m to SE. Wedges out to</td>
<td>Quartzose micaceous sandstone, siltstone, mudstone. Bedding medium to thick; strongly scour</td>
<td>Lower Jurassic</td>
</tr>
</tbody>
</table>
Major structuring of the basin sequence probably began in the Early Tertiary when, following a period of intense weathering, fluvial deposits accumulated in slowly subsiding synclines (Senior et al., 1978). The second major episode of structural events consists of gentle warping which occurred in Late Oligocene to Early Tertiary time. Some faulting probably postdated the warping. A summary of the stratigraphy of five wells studied is given in Appendix 1.

The first hydrocarbon discovery in the Cooper/Eromanga Basin was made in 1963 when commercial quantities of Permian gas was discovered at Gidgealpa. Since then hydrocarbon accumulations have been discovered in a number of stratigraphic units ranging from Early Permian to Early Cretaceous in age. Shale horizons above the Murta Member is regarded as a good regional seal for the Jurassic reservoirs (Armstrong and Barr, 1982) and the Triassic Nappamerri Formation forms a regional seal for the hydrocarbons trapped in the Permian section (Kantsler et al., 1983). However most of the stratigraphic intervals contain shale horizons of varying thickness which could act as seals for the localized traps.
CHAPTER 3

Concepts of Source Rock and the Genesis of Hydrocarbons

3.1 Origin of petroleum

Petroleum is a naturally occurring, highly complex mixture of mobile organic compounds and is composed predominantly of hydrocarbons. It is a widely accepted view that petroleum is derived from biological material deposited together with fine grained sediments in sedimentary basins. Advocates of inorganic origin theories believed that petroleum is formed from the hydrocarbons generated by the interaction of metal carbides and water.

The similarity between the chemical structure of petroleum compounds and some compounds commonly present in biological material strongly suggests a biogenic origin for at least the majority of petroleum deposits. Eisma and Jurg (1969) have summarized the evidence supporting the biological origin of petroleum.

A remarkable example of the chemical similarity between the petroleum components and the natural biological material is shown in chlorophyll-a, the universal green pigment present in plant cells.
Phytol (C$_{20}$H$_{39}$OH), a diterpinic alcohol, which is present as a side chain in chlorophyll-a, is postulated as the precursor of pristane and other saturated isoprenoid hydrocarbons which are invariably present in petroleum deposits and source rock extracts (Bendoraitis et al., 1962). Welte and Waples (1973) have proposed the following series of reactions for the transformation of phytol to isoprenoid hydrocarbons, pristane (C$_{19}$H$_{40}$) and phytane (C$_{20}$H$_{42}$).
Phytenic acid
Decarboxylation
[ -CO₂ ]
-CH₃

Pristene

[H] Reduction

Dihydrophytol

-CH₂OH

-CH₂OH

Phytane

Pristane
Breger (1960) and Kvenvolden (1966) concluded that the bulk of the hydrocarbons, particularly linear alkanes in petroleum are derived from fatty acids in biological materials. In general the group of compounds known as lipids (including fats, waxes, terpenoids and steroids) is regarded as the most important component contributing towards the generation of petroleum hydrocarbons. Marine organisms are known to generate paraffin compounds up to about C-21, whereas the land plants synthesize waxes up to C-37. Tissot and Welte (1978) expressed the view that predominantly land-derived organic matter with high contents of lignin and carbohydrates has a H/C low and is more aromatic in nature. Organic material mainly derived from marine phytoplankton has a comparatively high H/C ratio and is more of an aliphatic or alicyclic nature.

3.2 Types of organic matter

The organic matter in sedimentary rocks has divided into three main types, based on bulk chemical composition. This in turn can be related to the nature of the biological precursor and the specific paths of evolution during their post-accumulation transformation.

**Type-I** Organic Matter contains mainly aliphatic chains and few aromatic nuclei. The H/C ratio is high and consequently the potential for oil and gas generation is high. The main biological precursors of Type-I organic matter are algal lipids and organic matter enriched in lipids due to microbial activities.

**Type-II** Organic Matter is mainly related to marine organic matter deposited under reducing conditions but also include exinite rich organic matter like spores, pollens and cuticles. This type of organic matter has a H/C ratio lower than Type-I organic matter and correspondingly the oil and gas
generation potential is low. Type-II organic matter contains many aromatic and alicyclic rings.

Type-III Organic Matter is more aromatic and naphthenic in nature; H/C ratio is low and oil potential is poor. However it has a considerable gas potential at depth. This type of organic matter is derived mainly from the structured support tissues of terrestrial plants. The oil generation potential per unit mass of organic matter is low but the volumetric abundance of Type-III organic matter in sediment means that this type of organic matter is also likely to have played a significant role in the generation of crude oil currently reservoired in some sedimentary basins.

3.3 Concept of source rock

Tissot and Welte (1978) defined petroleum source rocks as those "that are, or may become, or have been able to generate petroleum". Three fundamental needs to define a petroleum source rock are:

i. the organic matter content;

ii. types of organic matter present; and

iii. level of thermal maturity attained by the organic matter.

Organic matter content may be determined by chemical or organic petrological techniques. Ronov (1958) estimated 0.5% organic carbon (chemically determined) as the critical lower limit hydrocarbon generation and migration to be effective for a shale type source rock. The equivalent limit for a carbonate type source is 0.3% organic carbon (Gehman, 1962). However these limits are only rough guides and not quantitative boundaries. Organic petrological techniques determine the organic matter content on the volumetric basis and the following approximate grades have been set for clastic rocks (the grading also being modified in relation to the maceral composition).
Total organic matter

2.0% - Very Good
1.0-2.0% - Good
0.5-1.0% - Fair
0.5% - Poor

Organic matter type is best assessed directly using optical methods (reflected white light, transmitted light and fluorescence-mode microscopy). Geochemical type determination is indirect and based on the interpretation of elemental abundance on a van Kievelen type diagram or interpretation of any other set of two or more type sensitive variables. Identification of different types of organic matter (macerals) and the estimation of their relative abundance is equally important in source rock evaluation. Although basically any maceral can generate hydrocarbons, the different macerals have varying hydrocarbon generation potential. In general hydrogen-rich macerals of the exinite group (e.g., algae, resins, spores, cuticles, cork tissues and organic exudation products) have a greater hydrocarbon generation potential than the macerals of the inertinite group (i.e., oxidized woody material, fungi, etc.), with the macerals of vitrinite group having intermediate potential.

The generation and emplacement of petroleum at the expense of sedimentary organic matter is a time/temperature dependant dynamic process, linked to the evolution of the sedimentary basin. The resultant thermal evolution changes the physical and chemical properties of organic matter in sediments. Basically these physico-chemical changes tend to stabilize the structure of the organic matter, at the elevated temperatures developed during deep burial, by eliminating side chains and thus relieving steric hindrance. These progressive reactions during the thermal evolution of organic matter are associated with gradational change but a number of stages can be recognized (Tissot and Welte, 1978).
Fig. 3.1 General scheme of hydrocarbon formation as a function of burial of the source rock (After Tissot and Welte, 1978)
i. During late diagenesis, heteroatomic bonds and functional groups are eliminated. Organic matter remains immature at this stage.

ii. During catagenesis hydrocarbon chains and cycles are eliminated. The bulk of crude petroleum is formed at this stage.

iii. During metagenesis, rearrangement occurs in the aromatic sheets of the residual organic matter. Gas is generated at this stage due to both the release of tightly bound small functional groups and the cracking and disproportionation of long chain hydrocarbons. The amount and the composition of hydrocarbon present in the source rock change progressively as a function of increasing thermal evolution (Figure 3.1).

3.4 Methods used in source rock evaluation

Changes in the physico-chemical properties of sedimentary organic matter in response to the increase in temperature are used as indication of the level of maturation. Conventional methods used in determining the level of thermal maturity can be grouped into two categories:

A. Optical Methods
   i) measurement of the reflectance of vitrinite grains associated with sediments;
   ii) degree of coalification of palynomorphs; and
   iii) changes in the fluorescence intensities of exinite macerals.

B. Chemical Methods
   i) pyrolysis of organic matter in sediments;
   ii) elemental analysis of organic matter;
   iii) determination of the solvent extractable organic matter in relation to the total organic matter;
   iv) composition of hydrocarbons in extracts;
   v) carbon preference index;
   vi) isoprenoid distribution in saturated hydrocarbons;
### Table 3.1 Principal methods used for source rock characterization and their degree of efficiency (Modified After Tissot and Welte)

<table>
<thead>
<tr>
<th>Class</th>
<th>Type of the analysis</th>
<th>Abundance of Organic Matter</th>
<th>Quality = type of Organic Matter</th>
<th>Maturation of Organic Matter</th>
<th>Correlation between Source-rock and Petroleum</th>
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</thead>
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<tr>
<td>Chemical (on rock)</td>
<td>Organic carbon</td>
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<td></td>
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<tr>
<td></td>
<td>Transmitted light</td>
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</tr>
<tr>
<td></td>
<td>(Palynofacies, alteration)</td>
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<td></td>
<td></td>
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<tr>
<td>Optical microscopy</td>
<td>Reflected light</td>
<td>xxx</td>
<td>xx</td>
<td>xx</td>
<td></td>
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<td></td>
<td>Fluorescence mode</td>
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<td>xxx</td>
<td>xxx</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Rock-Eval</td>
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<td>xx</td>
<td>xx</td>
<td></td>
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<tr>
<td>Pyrolysis (on rock)</td>
<td>Cₚ/Cₜ, etc. ...</td>
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<td>x</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Physicochemical (on kerogen)</td>
<td>Elemental analysis</td>
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<td>xx</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>Infrared spectroscopy</td>
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<td></td>
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<tr>
<td></td>
<td>Thermal analysis (TGA)</td>
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<td></td>
<td>Electron microdiffraction</td>
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<td></td>
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<td>Carbon isotopes</td>
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<td>x</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>Chemical (on bitumen or crude oil)</td>
<td>Amount of HC</td>
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<td>xx</td>
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<td>Light HC</td>
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<tr>
<td></td>
<td>n-Alkanes</td>
<td></td>
<td>x</td>
<td>x</td>
<td>x</td>
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<tr>
<td></td>
<td>Isoprenoids</td>
<td></td>
<td>x</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Steroids, terpenes</td>
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<td>x</td>
<td>x</td>
<td>XXX</td>
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<td></td>
<td>Porphyrins, metals</td>
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</tr>
<tr>
<td>Physical (on bitumen, oil, gas)</td>
<td>Carbon isotopes</td>
<td></td>
<td>x</td>
<td>x</td>
<td>xx</td>
</tr>
</tbody>
</table>

Efficiency:  xxx - Good or excellent;  xx - fair;  x - low or limitations of use.
vii) ring number distribution of naphthenes; and
viii) carbon isotope ratios.

Each of these methods has its own advantages and disadvantages in terms of the degree of reliability, reproducibility and practicality. Therefore it is desirable to use as many methods as possible since complimentary techniques give the most reliable assessment of the hydrocarbon generation potential of a source rock. Hood et al. (1975) proposed a single, continuous, numerical scale applicable over the entire thermal range of genesis and destruction of petroleum hydrocarbons called the "Level of Organic Metamorphism" (L.O.M.) to correlate most of the maturation parameters. Summaries of the uses and limitations of these parameters are given in Table 3.1 and Figures 3.2 and 3.3.

3.4.1 Optical methods

Vitrinite reflectance has long been used to determine coal rank (e.g., Rogers (1860), White (1915). Coal rank studies were extended to evaluate the thermal maturity of petroleum source rocks (e.g., Bartenstein and Teichmüller, 1974; Vassoyevich et al., 1969 and Lopatin, 1976). Rising temperature associated with increasing burial leaves an irreversible record on the immobile organic residue. For example, the changes in the reflectance of vitrinite. These properties, when properly interpreted give a reliable indication about the thermal history of the organic matter under investigation. However, reliable modelling of such data needs additional information such as geothermal gradients over time, subsidence curves (including the amount of post coalification cover loss), in addition to accurately measured rank data. Vassoyevich et al. (1973) calibrated the temperature equivalent zones of oil generation with vitrinite reflectance as

- principal zone of oil generation - 0.5-1.3% R_v;
- zone of maximum oil generation - 0.7-1.10% R_v.
Fig. 3.2 Comparison of various maturation indicators based on dispersed organic matter analysis (After Tissot and Welte, 1978).
Comparison of various maturation indicators based on the solvent extractable organic matter (After Tissot and Welte, 1978).
These values are subject to variations depending upon the nature of organic matter and the effective duration of heating. Powell and Snowden (1983) concluded that, in marine sourced Type III organic matter petroleum generation commences at $R_v$ 0.5 onwards whereas in terrestrial Type III organic matter, the generation of high wax hydrocarbons at the expense of cuticles, spores and pollens occurs at vitrinite reflectance values in excess of 0.7%. The colour changes in palynomorphs and changes in the fluorescence intensities of exinite macerals in response to the increase in burial temperatures are common optical methods used to supplement determination of the levels of thermal maturation by the vitrinite reflectance.

3.4.2 Physico-chemical methods

Pyrolysis, currently the most widespread chemical technique used to determine the level of maturity of sedimentary organic matter, has been described by several authors (e.g., Barker, 1974; Claypool and Reed, 1976; Espitalie et al., 1977). All pyrolysis techniques involve heating organic matter in an inert atmosphere at a programmed rate of temperature rise and measuring the yield of volatile products. The use of the ratios of the $S_1$ and $S_2$ peaks for volatile matter yield in determining the source rock maturity is shown diagrammatically in Figure 3.4a.

The elemental composition (H, C and O) of organic matter is related to the composition of its precursor but is modified during the first and second stages of coalification. With the progressive release of petroleum components as a response to increasing temperature, the elemental composition of the original sedimentary organic matter changes. Thus the elemental composition of the organic matter determined on a mineral-free basis, when plotted on a van Krevelen type diagram, gives a good indication of the (average) type (Figure 3.4B) as well as the status of thermal evolution (Figure 3.5) of the organic matter. The amount of solvent extractable organic matter in a
Fig. 3.4A Characterization of source rock maturity by pyrolysis methods (After Tissot and Welte, 1978).

Fig. 3.4B Classification of source rock types using hydrogen and oxygen indices (from Tissot and Welte, 1978).
Fig. 3.5 General scheme of the thermal evolution of organic matter presented on van Krevelon’s diagram (After Tissot and Welte, 1978).
source rock depends on the nature and amount of the organic matter present and its level of maturity. The bitumen ratio (i.e., ratio, total extractable organic matter/total organic carbon) tends to increase with increasing thermal maturity up to a certain limit and then decline. With the progressive generation of new hydrocarbons, the composition of the hydrocarbon fraction changes and such changes are used as a guide to maturity. The long chain n-alkanes in recent sediments show a strong odd predominance. The generation of new hydrocarbons by cracking gives equal amounts of odd and even numbered alkane so that with increasing maturity the odd even ratio tends to change. Such changes usually measured in terms of Carbon Preference Index (C.P.I.) of Bray and Evans (1961) and Odd Even Preference (O.E.P.) of Scalan and Smith (1970) are used as an indicator of thermal maturity. Similarly compositional changes in polycyclic naphthenes (Philippi, 1965) and isoprenoid content are used as indicators of the level of organic maturity.

The source potential of a stratigraphic horizon in a basin can be characterized in terms of organic matter abundance and level of thermal maturity. The only way to test the hypothesis that any given source rock has sourced particular crude oil is to compare the variables measured on the source rock with equivalent variables for crude oil. Migration, the connecting link between the source and reservoir, although widely studied, is one of the least understood phenomenon of petroleum generation and emplacement.

In this study it is proposed to use both organic petrological and organic geochemical methods to determine the source potential of the selected stratigraphic horizons from the Cooper/Eromanga Basin sequence in order to determine:

i. type and amount of organic matter present;

ii. levels of thermal maturity attained by the organic matter.
CHAPTER 4

Organic Petrology

The source potential of selected stratigraphic horizons was studied using the techniques of organic petrology. Selection of suitable intervals was done by studying well logs in particular the gamma-ray responses, neutron density, sonic and caliper logs.

4.1 Maturation Studies

The level of post depositional thermal maturity attained by the organic matter in the selected stratigraphic horizons was estimated by measuring the reflectance of associated vitrinite. The vitrinite occurs as dispersed organic matter, as coal or as both forms.

4.1.1 Sample preparation

A total of 124 samples including 15 drill core samples and 109 cutting samples were examined by organic petrological techniques. Samples were made into polished blocks using standard coal polishing techniques. Cutting samples were made into solid blocks in a cold setting resin. The blocks were then cut in vertical plane and the cut surfaces polished. Core samples were sawn and mounted so that the polished surface is perpendicular to the bedding plane.

4.1.2 Instrumental parameters

The vitrinite reflectance measurements were made using a Leitz
MPV1 photometer, a fluorite lens (n.a. 0.85), plane polarized light, refractive index of immersion oil, 1.518 at 23°C, wavelength 546nm and standards spinel 0.42%, YAG 0.92% and GGG 1.76%.

4.1.3 Results

The vitrinite reflectance data obtained from 124 samples are given in Table 4.1 together with their respective depths, corresponding formations and the well names. Owing to the very close spacing between several samples within the units sampled, it was necessary to obtain an average reflectance value for each sample interval before plotting the depth vs reflectance profiles. Figure 4.1 shows an example of close sample coverage within the potential source horizons in Jackson No.1. Figures 4.2, 4.3, 4.4, 4.5 and 4.6 show the generalized depth vs reflectance profiles for individual wells and the profiles of each "well group" are shown in Figures 4.7 and 4.8 for the purpose of comparison. The reflectance gradient data and the calculated model temperatures are given in the Tables 4.1 and 4.2.

4.2 Organic Matter Content

The concept of organic matter abundance factor (OMAF) is introduced to assess the relative abundance of organic matter types in ditch cuttings on a semiquantitative basis. The low percentage of important components in most of the samples examined, usually does not permit a reliable assessment of the organic matter abundance using conventional point counting techniques and hence the OMAF assessment method is proposed. Details of the OMAF determination procedures are given in Appendix 2. Definitions of abundance terms are also given in this Appendix. Figures 4.9, 4.10, 4.11, 4.12, and 4.13 show the OMAF
Table 4.1 - Jackson No.1.

<table>
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<tr>
<th>Sample No.</th>
<th>Depth</th>
<th>Formation/Unit</th>
<th>$R_{\text{vmax}}$</th>
<th>Range</th>
<th>N</th>
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<td>1099</td>
<td>Murta Member</td>
<td>0.44</td>
<td>0.36-0.49</td>
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<tr>
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* Core Sample
### Table 4.1 (continued)

**Naccowlah No. 1**

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* Core Sample
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Merrimelia No. 8

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Merrimelia No. 5

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Packsaddle No. 3

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Fig. 4.1 An example of close space sampling and the distribution of vitrinite reflectance data (Jackson No.1).
Fig. 4.2  Generalized depth vs. vitrinite reflectance profile - Jackson No.1.
NACCOWLAH No.1

Undifferentiated

Immature

Toolebuc

Roma

Transition

Murta

Namur

Westbourne

Adori

Birkhead

Hutton

Basal Jurassic

Nappamerri

Tooalchie

Patchawarra

Pre-Permian

T.D. 2118 m.

Depth in Km.

% Vitrinite reflectance

Fig. 4.3 Generalized depth vs vitrinite reflectance profile - Naccowlah No.1.
Fig. 4.4 Generalized depth vs vitrinite reflectance profile - Merrimelia no.8.
Fig. 4.5
Generalized depth vs vitrinite reflectance profile - Packsaddle No.3.
Fig. 4.6  Generalized depth vs vitrinite reflectance profile - Merrimelia No.5.
Fig. 4.7 Comparison of depth vs vitrinite reflectance profiles for Jacks on No.1 and Naccowlah No.1.
Fig. 4.8  Comparison of depth vs vitrinite reflectance profiles for Merrimelia No.8, Merrimelia No.5 and Packaddle No.3.
values of the individual maceral groups and the total dispersed organic matter (d.o.m.) content of the stratigraphic horizons sampled plotted as a function of depth, for Jackson No.1, Naccowlah No.1, Merrimelia No.8, Packsaddle No.3 and Merrimelia No.5, respectively. The organic matter types in different stratigraphic horizons are summarized below.

The oldest stratigraphic unit studied in the sequence, the Permian Merrimelia Formation, was examined in Packsaddle No.3 and Merrimelia No.5. The d.o.m. content of the Merrimelia Formation is low in Packsaddle No.3 with OMAF values usually less than 10 units. The predominant sandstone lithology is virtually barren of organic matter and the sparse organic matter present is largely confined to subordinate claystone lithologies. The minor carbonate facies is also devoid of organic matter.

The Merrimelia Formation in Merrimelia No.5 is also poor in organic matter. Of the 14 samples studied, only two samples (Nos. 16804 and 16806) had OMAF values for the d.o.m. above 10 units and the overall OMAF values for the formation are less than 5 units. However the presence of pyrite in the matrix of sandstone (Plate 1 and 2) could possibly indicate the early replacement of organic matter by pyrite. The rare d.o.m. present is inertinite dominated. The basement lithology examined does not appear to contain any organic matter (Plate 3).

Two samples examined from the undifferentiated Giogealpa Group (consisting of the Toolachee Formation, the Roseneath, Epsilon and Murteree Shales, the Patchawarra Formation and the Tirrawarra Sandstone) in the Merrimelia No.5 contained abundant d.o.m. with OMAF values over 50 units. The dispersed organic matter is inertinite-dominated but a substantial amount of vitrinite is
Fig. 4.9  Distribution of the O.M.A.F. values as a function of depth - Jackson No.1.
NACCOWLAH No. 1

Fig. 4.10 Distribution of the O.M.A.F. values as a function of depth - Naccowlah No.1.
Fig. 4.11 Distribution of the O.M.A.F. values as a function of depth - Merrimelia No.8.
Fig. 4.12 Distribution of the O.M.A.F. values as a function of depth - Packsaddle No. 3.
Fig. 4.13 Distribution of the O.M.A.F. values as a function of depth - Merrimelia No.5.
Plate 1. Heavily pyritized sandstone. Sample No. 16812. Merrimelia Formation, Lower Permian, Merrimelia No. 5, \( R_{\text{vmax}} \) n.a., field width 0.44 mm.

Plate 2. As for Plate 1, but in fluorescence mode.

Plate 3. Iron stained matrix in barren Innaminka Red Beds. Sample No. 16818, Merrimelia No. 5, \( R_{\text{vmax}} \) n.a., field width 0.34 mm.
Plate 4. Abundant sporinite in clarite. Note common oil cuts. Sample No. 15544, Patchawarra Formation, Lower Permian, Jackson No. 1. $R_{\text{y, max}}$ 0.87%, field width 0.34 mm.

Plate 5. As for Plate 4, but in fluorescence mode.

Plate 6. Well preserved sporangium in clarodurite. Sample No. 15542. Patchawarra Formation. Jackson No. 1. $R_{\text{y, max}}$ 0.87%, field width 0.36 mm.
Exinite is rare as d.o.m. with OMAF values is less than 10 units. A major fraction of the organic matter is contained in shaly coal lithologies but the remainder of the organic matter is evenly distributed in all lithological types. The Lower Permian Patchawarra Formation was examined only in the Jackson/Naccowlah area. In Jackson No.1, the Patchawarra Formation is d.o.m. rich with OMAF values around 40 units but most of the organic matter is inertinite. The coal examined from the Patchawarra Formation is vitrinite-rich and the gross composition is

<table>
<thead>
<tr>
<th>Maceral</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vitrinite</td>
<td>59%</td>
</tr>
<tr>
<td>Inertinite</td>
<td>31%</td>
</tr>
<tr>
<td>Exinite</td>
<td>5%</td>
</tr>
<tr>
<td>Mineral Matter</td>
<td>5%</td>
</tr>
</tbody>
</table>

Sporinite and cutinite form the main exinite macerals in the coal (Plates 4 and 5) but well preserved sporangia (Plates 6 and 7) and telalginite are also present in minor amounts. Oil cuts are common in Patchawarra coal in Jackson No.1. Organic matter is mostly concentrated in siltstone lithologies.

The Patchawarra Formation in Naccowlah No.1 is more coal rich, but the dispersed organic matter content is lower than in Jackson No.1. The Patchwarra coal in Naccowlah No.1 well is inertinite rich (Plates 8 and 9) and the gross composition is

<table>
<thead>
<tr>
<th>Maceral</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vitrinite</td>
<td>34%</td>
</tr>
<tr>
<td>Inertinite</td>
<td>57%</td>
</tr>
<tr>
<td>Exinite</td>
<td>4%</td>
</tr>
<tr>
<td>Mineral Matter</td>
<td>5%</td>
</tr>
</tbody>
</table>

Exinite fluorescence colours are very dull. The d.o.m. is inertinite dominant and vitrinite is predominant over exinite. The d.o.m. is largely confined to shaly coal and fine grained lithologies.
except in the upper part of the formation where d.o.m. is more evenly distributed in all lithologies.

The Roseneath Shale was studied only in Jackson No.1 (4 samples). The d.o.m. is abundant with OMAF values above 40. The main maceral group is exinite consisting predominantly of telalginite (Plates 10, 11, 12 and 13). The fluorescence colours of telalginite are relatively intense despite the levels of thermal maturity attained. Other exinite macerals consist mainly of sporinite and cutinite with rather dull fluorescence colours. The d.o.m. is mostly enriched in the fine grained lithologies but subordinate sandstone facies are poor in organic matter. Inertinite is predominant over vitrinite.

The Permian Toolachee Formation was studied in both Jackson No.1 (4 samples) and Naccowlah No.1 (6 samples). In both wells the Toolachee Formation samples are very rich in organic matter. The top sample examined from the Toolachee Formation in Jackson No.1 is a core sample of coal rich in vitrinite and the composition is as follows:

- Vitrinite 52%
- Inertinite 30%
- Exinite 10% and
- Mineral Matter 8%

The dispersed organic matter is mostly confined to the shaly coal and other fine grained lithologies. Inertinite forms the main maceral group with exinite predominant over vitrinite (Plate 14). Large telalginite colonies are common in the shaly coal (Plates 15 and 16) and the exinite fluorescence is dull orange in colour (Plates 17 and 18) with the exception of telalginite which is bright yellow orange. The OMAF values for the total d.o.m. is above 40 units.

Similarly the Toolachee Formation in Naccowlah No.1 is also rich in dispersed organic matter. The OMAF values for the formation is
Plate 7. As for Plate 6, but in fluorescence mode.

Plate 8. Ornamented megaspore in vitrinitite (V.). Sample No. 15658, Patchawarra Formation. Naccowlah No.1, $R_{vmax}$ 0.90%, field width 0.56 mm.

Plate 9. As for Plate 8, but in fluorescence mode.
Plate 10. Abundant telalginite and dull fluorescing liptinite in inertinite rich shaly coal. Sample No. 15539. Roseneath Shale, Lower Permian, Jackson No.1, $R_v$ max 0.76%, field width 0.34mm.

Plate 11. As for Plate 10, but in fluorescence mode.

Plate 12. Inertinite and a large colony of telalginite in claystone. Sample No 15538, Roseneath Shale, Jackson No.1, $R_v$ max 0.74%, field width 0.28mm.
Plate 13. As for Plate 12, but in fluorescence mode.

Plate 14. Well preserved inertinite (relict xylem fibre in L.S.? in vitrinertite (I). Sample No.15469, Toolachee Formation, Upper Permian, Jackson No.1, R$_{\text{vmax}}$ 0.73%, field width 0.36mm.

Plate 15. Inertinite, vitrinite and a colony of telalginite in shaly coal. Sample No.15471, Toolachee Formation, Jackson No.1, R$_{\text{vmax}}$ 0.72%, field width 0.34mm.
Plate 16. As for Plate 15, but in fluorescence mode.

Plate 17. Abundant sporinite and cutinite in inertinite dominated shaly coal. Sample No. 15472, Toolachee Formation, Jackson No. 1, $R_v$ max 0.65%, field width 0.44 mm.

Plate 18. As for Plate 17, but in fluorescence mode.
over 40 units and like in the Jackson field, the organic matter is inertinite dominated but the exinite is subordinate to vitrinite. The dispersed organic matter content tends to be higher in fine grained lithologies and shaly, coal but a substantial amount of organic matter also occurs in sandstone lithologies. The composition of the coal examined in the Toolachee Formation in Naccowlah No.1 is different to that of Jackson No.1, having more inertinite. The gross composition is:

- Vitrinite 37%
- Inertinite 58%
- Exinite 2% and
- Mineral Matter 3%.

Elongated dull fluorescing resinite bodies are common in coal (Plates 19 and 20).

The Triassic Nappamerri Formation was studied in Merrimelia No.5 (3 samples) and Merrimelia No.8 (1 sample). Two of the drill core samples studied in Merrimelia No.5 did not contain any measurable vitrinite. The lithology consists of claystone with thin bands of sandstone and pods of carbonate. Organic matter is rare and, where present, consists mainly of inertodetrinite confined to claystone. Rare exinite macerals constitute dull orange fluorescing sporinite and liptodetrinite. The third drill core sample examined (depth 2267m KB) from the Nappamerri Formation in Merrimelia No.5 is a coal sample composed of an interbedded layer of vitrinertite (I), vitrite, clarodurite and inertite. The inertite bands consist mostly of semifusinite with little well preserved fusite. The cell lumens in fusite are commonly filled with carbonate minerals (Plates 21 and 22). The clarodurite bands contain abundant, dull fluorescing sporinite and cutinite (Plates 23 and 24). One drill core sample was
studied from the Nappamerri Formation in Merrimelia No.8 (depth 2168 m KBO and the sample contains no detectable exinite or vitrinite. Lithology consists of fine siltstone with patches of carbonate and the rare d.o.m. where present in inertodetrinite.

The basal Jurassic unit was studied in Merrimelia No.8 (3 samples) and Naccowlah No.1 (3 samples). The basal Jurassic unit in Merrimelia No.8 is coal rich and contains abundant d.o.m. with OMAF values over 40 units. Organic matter is vitrinite dominated with exinite predominant over inertinite (Plates 25 and 26). Organic matter is mainly confined to siltstone and shaly coal lithologies with minor amounts occurring in sandstone and claystone lithologies. The d.o.m. in the basal Jurassic unit in Naccowlah No.1 is comparatively low with OMAF values between 15-20 units. The d.o.m. is vitrinite rich with inertinite predominant over exinite; it occurs mainly in siltstone lithologies. Coal lithologies are sparse and consist predominantly of vitrite.

The Hutton Sandstone was examined in Packsaddle No.3 (3 samples). The OMAF values for the total d.o.m. is over 15 units and is highest among the samples studied in the Packsaddle section. The sampled interval is sandstone rich with a substantial amount of fine grained lithologies. Fine grained lithologies contain more organic matter than the sandstone. The d.o.m. is vitrinite dominated with inertinite predominant over exinite. Exinite macerals consist mainly of orange to dull orange fluorescing sporinite, cutinite and liptodetrinite. Coal lithotypes are common and include vitrite, duroclarite and clarite often rich in exinite (Plates 27 and 28). One core sample was also examined from the Hutton Sandstone in Jackson No.1 and contained no dispersed organic matter but does contain sporadic strings of vitrinite.
Plate 19. Elongated lens of resinite among exinite in clarodurite. Sample No. 15663, Toolachee Formation, Naccowlah No. 1, $R_{vmax}$ 0.92%, field width 0.34mm.

Plate 20. As for Plate 19, but in fluorescence mode.

Plate 21. Fusinite with carbonate filling the lumens. Sample No. 16816, Nappamerri Formation, Lower Triassic, Merrimelia No. 5, $R_{vmax}$ 0.82%, field width 0.34mm.
Plate 22. As for Plate 21, but in fluorescence mode.

Plate 23. Dull fluorescing exinite in duroclarite. Sample No.16816, Nappamerri Formation, Merrimelia No.5, $R_{v,\text{max}}$ 0.82%, field width 0.34 mm.

Plate 24. As for Plate 23, but in fluorescence mode.
Plate 25. Abundant cutinite and vitrinite in sandstone. Sample No.15437, Basal Jurassic Units, Lower Jurassic, Merrimelia No.8, $R_{vmax}$ 0.66%, field width 0.22mm.

Plate 26. As for Plate 25, but in fluorescence mode.

Plate 27. Cutinite rich clarite with semifusinite. Sample No.15717, Hutton Sandstone, Lower Jurassic, Packsaddle No.3, $R_{vmax}$ 0.65%, field width 0.22mm.
The Birkhead Formation, studied in Merrimelia No.8 (4 samples) and Packsaddle No.3 (9 samples), showed a highly variable organic matter content. In Merrimelia No.8 the OMAF values for the total d.o.m. range from 20 to 30 units whereas in Packsaddle No.3 they range from 10 to 20 units. The Birkhead Formation in Merrimelia No.8 is sandstone dominated. Although fine grained lithologies contain abundant organic matter, the sandstone lithologies also contain a substantial amount of organic matter (Plates 29, 30, 31, and 32). The d.o.m. is vitrinite-rich and exinite is predominant over inertinite. The main exinite macerals present are yellow to orange fluorescing sporinite, cutinite and liptodetrinite. Phytoplanктон are rarely present. Suberinite is abundant in both coal and shaly coal. Coal lithologies are sparse and clarite forms the main microlithotype, predominant over vitrite. The Birkhead Formation in Packsaddle No.3 is also sandstone-rich but a substantial amount of fine grained lithologies is also present, particularly in the middle part of the formation (Plates 33 and 34). In the upper part the d.o.m. is evenly distributed between the coarse and fine grained lithologies but the d.o.m. content tends to decrease in the middle part of the formation with increase in the claystone content. The d.o.m. is vitrinite rich and inertinite is predominant over exinite. The exinite macerals consist of orange to dull orange fluorescing sporinite, cutinite and liptodetrinite. Both fluorinite and telalginite are rare and resinite is common in coal. Coal lithologies are sparse and consist mainly of vitrite and clarite often rich in well preserved cutinite (Plates 35 and 36).

The Westbourne Formation was studied in Jackson No.1 (3 samples), Packsaddle No.3 (5 samples) and in Merrimelia No.8 (3 samples). The
OMAF values for the total d.o.m. is lowest in Jackson No.1 (less than 5 units) and is also low in Packsaddle No.3 (5-10 units). The OMAF values are slightly higher for the Westbourne Formation in Merrimelia No.8. In Jackson No.1, the Westbourne Formation consists mainly of barren sandstone and the subordinate claystone facies is also generally poor in organic matter but some claystones are rich in inertinite (Plate 37 and 38). Rare exinite includes dull fluorescing sporinite, cutinite, liptodetrinite and light brown fluorescing bitumen. The organic matter in the Westbourne Formation in Merrimelia No.8 and Packsaddle No.3 is also inertinite dominated and largely confined to the claystone lithologies. Exinite fluorescence is dull.

The Namur Sandstone Member was examined only in Packsaddle No.3 (2 samples). The OMAF values for the total d.o.m. in the samples ranges between 15 and 25 units. The dominant sandstone lithologies are poor in organic matter, but the subordinate fine grained lithologies contain a substantial amount of organic matter. The organic matter is exinite rich and inertinite is predominant over vitrinite.

The Murta Member is the youngest stratigraphic level sampled in the Eromanga Basin sequence. This formation was sampled in Jackson No.1 (17 samples), Naccowlah No.1 (8 samples), Merrimelia No.8 (1 sample) and in Packsaddle No.3 (8 samples). The Murta Member in Jackson No.1 generally has a low OMAF value for the total d.o.m. (around 10 units), whereas the values are slightly higher in Naccowlah No.1 (10-15 units). The organic matter tends to be concentrated in the siltstone lithologies as compared with the sandstone and claystone lithologies. The exinite macerals present include yellow to orange fluorescing cutinite (Plates 39 and 40), sporinite, liptodetrinite and rare yellow to orange fluorescing telalginite. Fluorinite is rare and
Plate 28. As for Plate 27, but in fluorescence mode.

Plate 29. Abundant d.o.m. in sandstone consisting mainly of vitrinite, cutinite and sporinite. Sample No. 15432, Birkhead Formation, Middle Jurassic, Merrimelia No. 8, $R_{vmax}$ 0.57%, field width, 0.22 mm.

Plate 30. As for Plate 29, but in fluorescence mode.
Plate 31. Abundant exinite and vitrinite in claystone. Sample No.15434, Birkhead Formation, Merrimelia No.8, $R_{v\text{max}}$ 0.60%, field width 0.34mm.

Plate 32. As for Plate 31, but in fluorescence mode.

Plate 33. Pyrite replacing organic matter in the matrix of sandstone. Sample No.15716, Birkhead Formation, Packsaddle No.3, $R_{v\text{max}}$ 0.56%, field width 0.44mm.
Plate 34. As for Plate 33, but in fluorescence mode.

Plate 35. Coal fragment of clarite composition in sandstone. Sample No. 15679, Birkhead Formation, Packsaddle No. 3, $R_{\text{vmax}}$ 0.52%, field width 0.44 mm.

Plate 36. As for Plate 35, but in fluorescence mode.
Plate 37. Abundant inertodetrinite and sparse exinite in claystone. Sample No. 15464, Westbourne Formation, Upper Jurassic, Jackson No. 1, $R_{max} 0.52\%$, field width 0.34 mm.

Plate 38. As for Plate 37, but in fluorescence mode.

Plate 39. Cutinite and vitrinite in sandstone. Sample No. 15457, Murta Member, Upper Jurassic, Jackson No. 1, $R_{max} 0.54\%$, field width 0.56 mm.
Plate 40. As for Plate 39, but in fluorescence mode.

Plate 41. Fluorinite with an oil halo in shaly coal and greenish yellow fluorescing sporinite and liptodetrinite. Sample No.15590, Murta Member, Upper Jurassic, Naccowlah No.1, $R_{y_{max}}$ 0.33%, field width 0.22mm. photographed in fluorescence mode.

Plate 42. Preserved cellular texture in vitrinite. Sample No.15590, field width 0.34 mm.
Plate 43. Secondary exudatinite filling the fractures in a vitrinite grain. Sample No.15597, Murta Member, Naccowlah No.1, $R_{\text{vmax}}$ 0.57%, field width 0.56 mm.

Plate 44. As for Plate 43, but in fluorescence mode. Note weak oil cut (greenish fluorescence) in vitrinite.

Plate 45. Abundant d.o.m. consisting mainly of vitrinite, cutinite, sporinite and inertodetrinite in siltstone. Sample No.15439, Murta Member, Merrimelia No.8, $R_{\text{vmax}}$ 0.48%, field width 0.22 mm.
Plate 46. As for Plate 45, but in fluorescence mode.

Plate 47. Telalginite, cutinite and sporinite in coarse siltstone. Also note sparse inertodetrinite and fine vitrinite. Sample No.15667, Murta Member, Packsaddle No.3. \( R_{vmax} 0.45\%, \) field width 0.22mm.

Plate 48. As for Plate 47, but in fluorescence mode.
generally confined to shaly coal (Plate 41). Sparse bitumen is found, often diffused in the matrix of sandstone. Coal lithologies are rare and consist mainly of vitrite, often showing a relict cellular texture (Plate 42). Early mobilization of hydrocarbon rich material is exemplified by the presence of exudatinite in fillings, and faint oil cuts from the coal grains from Naccowlah No.1 (Plates 43 and 44). Vitrinite usually forms the main maceral group with inertinite predominant over exinite.

The Murta Member contains more organic matter in the Merrimelia/Packsaddle area when compared with Jackson/Naccowlah area. The OMAF (d.o.m.) values for Merrimelia No.8 sample is over 50 units with exinite values over 30 units. The average OMAF values for the total d.o.m. in Packsaddle samples vary between 15 and 20 units. Exinite in the Merrimelia No.8 sample consists mainly of sporinite, cutinite (Plates 45 and 46) and sparse telalginite. Inertinite is predominant over vitrinite and is constituted mainly of inertodetrinite. The organic matter in the Murta Member of these wells also tends to be concentrated in silty lithologies. The exinite in Packsaddle No.3 consists of dull yellow to orange fluorescing cutinite, sporinite, liptodetrinite and rare bright orange fluorescing telalginite (Plates 47 and 48). Resinite and fluorinite are rare. Claystone lithologies are generally rich in inertinite and the fluorescence of exinite macerals in claystone is usually dull when compared with the exinite in coarse grained lithologies. Coal is rare and consists mainly of vitrite and clarite.
4.3 Discussion

4.3.1 Thermal History

For the Jackson/Naccowlah well pair, the Jurassic reflectance gradient is low to moderate for Jackson No.1 (0.13-0.39% $R_{v\max}/km$) and is moderate for Naccowlah No.1 (0.31-0.75% $R_{v\max}/km$). The Permian reflectance gradient is moderate to high for Naccowlah No.1 (0.96-1.34% $R_{v\max}/km$) but consistently high for Jackson No.1 (1.01-1.70% $R_{v\max}/km$). For the Merrimelia/Packsaddle well group, the Jurassic reflectance gradient is low to moderate for Merrimelia No.8 (0.29-0.56% $R_{v\max}/km$) and Packsaddle No.3 (0.34-0.71 $R_{v\max}/km$). No reflectance data are available for the Permian section due to the location of both of these wells near the crests of their respective structures. The Permian section examined in the Merrimelia No.5 (down-structure from Merrimelia No.8) showed a moderate reflectance gradient (0.37-0.63% $R_{v\max}/km$).

Vitrinite reflectance data suggest that the stratigraphic sequence in Jackson No.1 reached the oil window at a depth of 1250m KB corresponding to the base of Namur Sandstone Member (vitrinite reflectance of 0.5%). The peak zone of oil generation (vitrinite reflectance 0.7-0.9%) for the same sequence lies between 1550-1650m and contains the lower part of the Toolachee Formation, Roseneath Shale and the top of the Patchawarra Formation. In Naccowlah No.1, the oil window is reached at a depth of 1500m corresponding to the lower part of the Namur Sandstone Member. The peak zone of oil generation appears to lie between 1700-2000m depth enveloping the lower part of the Hutton Sandstone, the basal Jurassic, Toolachee and the upper half of the Patchawarra Formations. Petrological evidence suggests that
Table 4.2 - Reflectance Gradient Data

<table>
<thead>
<tr>
<th>Well No.</th>
<th>Temperature Gradient °C/km</th>
<th>Jurassic/Triassic Reflectance Gradient % Rv/km</th>
<th>Permian Reflectance Gradient % Rv/km</th>
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<tbody>
<tr>
<td>Jackson No.1</td>
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<td>0.13-0.39</td>
<td>1.01-1.70</td>
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<tr>
<td>Naccowlah No.1</td>
<td>46</td>
<td>0.31-0.75</td>
<td>0.96-1.34</td>
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<td>Merrimelia No.8</td>
<td>-</td>
<td>0.29-0.56</td>
<td>-</td>
</tr>
<tr>
<td>Packsaddle No.3</td>
<td>-</td>
<td>0.34-0.71</td>
<td>-</td>
</tr>
<tr>
<td>Merrimelia No.5</td>
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<td>-</td>
<td>0.37-0.63</td>
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Table 4.3
Calculated and Observed Temperatures

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<tr>
<th>Well</th>
<th>Depth (m)</th>
<th>( R_{v\text{max}} )</th>
<th>T. present (°C)</th>
<th>T. iso (°C)</th>
<th>T. grad (°C)</th>
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<td>62</td>
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the Pre-Permian basement forms the probable lower limit of the economic hydrocarbon preservation in both wells.

For the area of Merrimelia/Packsaddle structures, the Merrimelia No.8 section has reached the level of maturity adequate for the inception of oil generation at a depth of 1650m corresponding to the base of Namur Sandstone Member (0.50% $R_{v\text{max}}$) and the peak zone of generation lies below 2100m enclosing organic matter poor Triassic Nappamerri Formation. Only the pre-Jurassic section was examined in Merrimelia No.5 and this appears to lie within the peak zone oil generation. The section examined covers the organic matter rich, but relatively thin Gidgealpa Group, and the organic matter poor Nappamerri and Merrimelia Formations. In Packsaddle No.3, the oil window correspond at 1750m (middle of Birkhead Formation). The peak zone of oil generation lies below 2100m enclosing parts of the near barren Nappamerri Formation and equally organic matter poor Merrimelia Formation. The pre-Permian basement probably forms the economic basement for the hydrocarbon preservation in all three wells.

A comparison of the thermal histories of the Jackson No.1/Naccowlah No.1 well pair based on vitrinite reflectance data suggests the following:

(a) the present day burial depth varies for the same formation, which has similar vitrinite reflectance values. The cause for this observation is not clear. Kantsler et al (1983) concluded that the thermal history of Cooper/Eromanga Basin is highly variable and the isoreflectance surfaces show varying relationships to regional structure and present day temperature gradient variations (Figure 4.14).

(b) The Permian reflectance gradient in Jackson No.1 is higher than that of Naccowlah No.1. This could mean that the Permian coalification in the Jackson No.1 site occurred under more
Fig. 4.14 Schematic cross sections through Cooper/Cromanga Basin showing the variations in the isoreflectance surfaces (After Kantsler et al., 1983).
elevated geothermal gradients as compared to Naccowlah No.1. However the slope of the Permian profile suggests that in Jurassic time, the Lower Permian section in Jackson No.1 has already passed the incipient phase of hydrocarbon generation. Pitt (1982) suggested that in the Cooper Basin, oil generation from the Permian did not commence until, at least, the mid Jurassic and possibly as late as Cretaceous. Kantsler et al. (1983) expressed the view that the main phase of oil generation in the Permian section commenced in Cenomanian time. The Naccowlah section probably reached the same level of maturity much later in the Jurassic. Kantsler et al. (1983) suggested that the basal Hutton - basal Jurassic source rocks in the central Patchawarra Trough commenced significant oil generation in the Tertiary to Recent time.

(c) The sudden inflection of the reflectance profile of Jackson No.1 in the lower Jurassic section may be indicative of the diminishing effects of a localized Permian to Jurassic thermal event.

(d) Post-Permian reflectance gradients are comparable in both wells and this can be interpreted as sedimentation and coalification under comparatively low, stable and comparable geothermal gradients.

(e) the present day geothermal gradient of Jackson No.1 (50°C/km) is slightly higher than that of Naccowlah No.1 (46°C/km).

(f) For the Merrimelia and Packsaddle structures, the Mesozoic reflectance profiles are nearly parallel, with moderate reflectance gradients. The Permian reflectance gradient in Merrimelia No.5 also lies on a trend similar to that in the overlying Mesozoic. The near linear reflectance profiles with moderate slopes and without any appreciable curvature is
characteristic of continuous sedimentation under a low but constant geothermal gradient in both Merrimelia and Packsaddle wells. The presence of areas with considerably elevated pre-Jurassic geothermal gradients, as well as areas which do not show any evidence of such thermal events, in the central Cooper/Eromanga Basins has been described by Kantsler et al. (1978).

4.3.2 Source Potential

The source potential of the stratigraphic sequence (based on petrological data for the organic matter abundance) examined from the Cooper/Eromanga Basin sequence in five wells under review has been discussed in Section 4.3.1. This information is summarized in Figure 4.15.

The source rating is based on the OMAF values with the following intervals.

Poor - OMAF values less than 15
Fair - OMAF values range between 15-20
Good - OMAF values range between 20-40
Very Good - OMAF values greater than 40.

The following features are clear in this diagram:

i. the same formation may not have the same source potential at different locations within the same sedimentary basin;

ii. the Mesozoic section in the Merrimelia/Packsaddle area is more enriched in organic matter and hence has a better source potential than the Mesozoic section in Jackson/Naccowlah area;

iii. the pre-Mesozoic section, namely the Gidgealpa Group in the Jackson/Naccowlah area is very rich in organic matter and has a very good source potential (this section is absent in Merrimelia
Comparison of the source potential of the different stratigraphic horizons studied in the Cooper/Eromanga Basin sequence.
iv. comparing Merrimelia No.8 and Packsaddle No.3 the source potential of the Mesozoic section in Merrimelia No.8 is better than that in Packsaddle No.3;

v. comparing Jackson No.1 and Naccowlah No.1, the Permian source potential in Jackson No.1 is better than Naccowlah No.1; and

vi. in general, the Westbourne, Nappamerri and Merrimelia Formations have poor source potential.

Kantsler et al. (1983) concluded that within the Cooper/Eromanga Basin sequence, fair to good, and locally rich, source rocks occur throughout the Permian section and locally within the Jurassic section. Cook (1982) grouped the formations within the Mesozoic Eromanga Basin sequence into four main organic facies based upon the composition of coal and coal-related organic matter.

The Murta Member has a poor source potential on average in the Jackson/Naccowlah area, despite the presence of minor siltstone lithologies, rich in exinite. The source potential of the same formation is good to very good in Packsaddle and Merrimelia No.8. The Murta Member in Merrimelia No.8 contains abundant exinite consisting of cutinite, sporinite and liptodetrinite together with sparse telalginite. The vitrinite reflectance values indicate that the formation is immature to marginally mature ($R_{\text{v max}} = 0.48$). Snowden and Powell (1982) describe the generation of light oil and condensate from some kinds of terrestrial organic matter at levels of thermal alteration ranging from 0.45 to above 1.0% vitrinite reflectance in Canadian frontier basins. However, their model solicits a resinite content of about 10% and resinite is rare in the Murta Member. It is unlikely that hydrogen rich telalginite has contributed substantially towards the hydrocarbons generated in Murta because:
(a) telalginite appears to need to attain a maturation level of about 0.70% vitrinite reflectance for the generation of significant hydrocarbons; and

(b) neither Murta Member extracts or the Mesozoic oils show any predominance of linear alkanes in C29 range, a product typical of *Botryococcus* type algae.

Nevertheless it may be possible that the Murta Member had generated some hydrocarbons in the areas where it is rich in organic matter. The thermocatylitic decomposition reactions may not be completed but the generation of light hydrocarbons involving lower activation energies cannot be ruled out.

The Namur Sandstone examined in Packsaddle No.3 has a fair source potential but the sampled interval is only a thin organic rich siltstone band. The Westbourne Formation examined in Merrimelia No.8, Packsaddle No.3 and Naccowlah No.1 showed a poor source potential.

The Birkhead Formation in Merrimelia No.8 has good source potential, mainly due to vitrinite, but a significant amount of exinite and inertinite also occurs. The same formation has a poor source potential in the Packsaddle No.3 indicating the discontinuous nature of the distribution of the quality and quantity of organic matter within one single source bed. The Birkhead Formation in Merrimelia No.8 is mature enough for the incipient generation of hydrocarbon ($R_{\text{vmax}}$ 0.52%) and, with a stratigraphic thickness of over 60 metres, may have contributed towards the oil generated and reservoired in the Mesozoic of Merrimelia No.8.

The Hutton Sandstone in Jackson No.1 has a poor source potential but it constitutes the best Mesozoic reservoir in the Jackson field. However a fair source potential is present in the lower part of the Hutton Sandstone in Packsaddle No.1. The organic matter is vitrinite and inertinite rich. The level of thermal maturity of the organic
matter is adequate ($R_{max} \approx 0.62\%$), but this source potential is restricted to the bottom ten metres of the 175m thick stratigraphic sequence and may not have significant potential on a regional scale.

The basal Jurassic unit in Merrimelia No.8 has the best source potential (rated good) in the section studied in that well. The organic matter is vitrinite- and inertinite-rich but a significant amount of exinite, consisting mainly of sporinite, cutinite, liptodetrinite and suberinite.

The level of thermal maturity is near the peak zone of oil generation ($0.69\% R_{max}$) and the organic rich basal Jurassic formation is likely to have played a major role in the oil generation within the Mesozoic section in Merrimelia No.8. The same formation at Naccowlah No.1 shows only poor to marginally fair source potential.

The Nappamerri Formation in Merrimelia No.8 and in Merrimelia No.5 has a poor source potential. The Permian Gidgealpa Group shows the best source potential on the Jackson/Naccowlah area, but when present, also has very good source potential in Merrimelia/Packsaddle area, e.g., Merrimelia No.5. The Toolachee Formation has very good source potential in both Jackson No.1 and Naccowlah No.1 but is marginally better in Jackson No.1 due to the presence of abundant sporinite, cutinite and sparse telalginite, a group of hydrogen rich macerals with high hydrocarbon generation potential at the maturity levels of $0.70-0.90\%$ vitrinite reflectance. The average reflectance value for the Toolachee Formation in Jackson No.1 is $0.72\%$ and $0.80\%$ in Naccowlah No.1. The average thickness of the formation is around 80 meters in both wells and thus it may have contributed substantially towards the liquid hydrocarbon generation in the Jackson field.

The Roseneath Shale Formation in Jackson No.1 although stratigraphically thin (23 meters thick in Jackson No.1) is consistently rich in organic matter, particularly in telalginite and
other terrestrial liptinite macerals. The level of vitrinite reflectance in this formation is 0.82%, a level of maturity adequate to generate hydrocarbons from all exinite macerals. Hence, it is postulated that the Roseneath Shale formation too had a significant role in the hydrocarbon genesis in Jackson area.

The Patchawarra Formation has very good source potential in Jackson No.1 and the source potential is lower at Naccowlah No.1. The dispersed organic matter is inertinite-dominated but a substantial amount of desmocollinite and faintly fluorescing exinite is also present. Smyth (1979) concluded the Patchawarra Formation in the Fly Lake-Brolga area of the Cooper Basin contains plentiful dispersed organic matter, where exinite d.o.m. occurs almost exclusively near the top of the formation with vitrinite material predominating in the middle and lower sections. The level of maturity attained by the Patchawarra Formation in Jackson No.1 is about 0.88% $R_{vmax}$ and 0.90% $R_{vmax}$ in Naccowlah No.1, both wells are still in the zone of peak oil generation for abundant desmocollinite although the predominant inertinite may have lost most of its volatile components. The Patchawarra Formation is also classified as a potential Permian source horizon in the Jackson/Naccowlah area.

The undifferentiated Gidgealpa Group in Merrimelia No.5 also shows very good source potential due to the presence of abundant organic matter. Although organic matter is inertinite-dominated, significant vitrinite and sparse exinite is also present and at the level of thermal maturity of 0.74% vitrinite reflectance these macerals are still capable of generating significant amounts of hydrocarbons.

The Merrimelia Formation in both Packsaddle No.3 and Merrimelia No.5 does not show any significant source potential.
CHAPTER 5
Crude Oil Geochemistry

Nine crude oil samples and one "condensate" sample recovered from Mesozoic reservoirs in the study area were analysed using standard organic geochemical methods. The details of the sample locations are given in Table 5.1. Crude oil from the Hutton reservoir in Naccowlah South No.1 was only partially analysed as the discovery was made when this work was near completion.

5.1 Experimental

Except for the "condensate" sample from Chookoo No.1, the crude oil samples were topped to 210°C by distillation and the fractions boiling above 210°C were analysed. Asphaltenes were precipitated by dissolving oil (approximately 0.1gm) in redistilled n-hexane and the solution was filtered using a teflon filter film. The asphaltene fractions were dried in a desiccator and weighed. The asphaltene-free fractions were separated into saturated hydrocarbons, aromatic hydrocarbons and polar compounds using elution column chromatography on a column packed with 58gm of silica gel and 23gm of activated alumina. The saturated fractions were eluted with n-hexane and the aromatic fractions were eluted with a 30:70 mixture of dichloromethane and n-hexane. The polar fractions were eluted with dried methanol. The eluted fractions were first concentrated by rotary evaporation and then evaporated under nitrogen. The individual fractions were gravimetrically quantitated after evaporating the solvent.
Table 5.1 - Location of Crude Oil Samples

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Well</th>
<th>Reservoir</th>
<th>Depth (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Merrimelia No.8</td>
<td>Namur Sandstone</td>
<td>1597-1609</td>
</tr>
<tr>
<td>2</td>
<td>-do-</td>
<td>Hutton Sandstone</td>
<td>1859-1879</td>
</tr>
<tr>
<td>3</td>
<td>Jackson No.1</td>
<td>Murta Member</td>
<td>1105-1113</td>
</tr>
<tr>
<td>4</td>
<td>Jackson No.3</td>
<td>Westbourne Fm</td>
<td>1342-1357</td>
</tr>
<tr>
<td>5</td>
<td>Jackson No.2</td>
<td>Hutton Sandstone</td>
<td>1442-1451</td>
</tr>
<tr>
<td>6</td>
<td>Gunna No.1</td>
<td>Murta Member</td>
<td>1204-1211</td>
</tr>
<tr>
<td>7</td>
<td>Gunna No.1</td>
<td>Hutton Sandstone</td>
<td>1518-1526</td>
</tr>
<tr>
<td>8</td>
<td>Chookoo No.1</td>
<td>*Hutton Sandstone</td>
<td>1693-1713</td>
</tr>
<tr>
<td>9</td>
<td>Chookoo No.1</td>
<td>Hutton Sandstone</td>
<td>1721-1724</td>
</tr>
<tr>
<td>10</td>
<td>Naccowlah South No.1</td>
<td>Hutton Sandstone</td>
<td>1670-1682</td>
</tr>
</tbody>
</table>

* Condensate

Branched plus cyclic alkane fractions were separated from the saturated hydrocarbons by refluxing aliquots of the saturated fractions with a 5°A molecular sieve (pre-heated at 300°C overnight) for 12 hours in redistilled cyclohexane.

The fractions, total saturates, branched plus cyclic, and aromatic were examined for molecular types present using gas chromatography with the following instrumental parameters.
Gas Chromatograph: Varian Model 3700

Recorders: (1) Omnicribe recorder - Houseton Instruments
(2) 3390A Integrator - Hewlett Packard

Column Specifications: Type: 25QC 3/BP 5-1.0
Length: 25 meters
Coating: Quartz-fused silica

Carrier gas: Helium

Back Pressure: (AP) at 50°C = 14 lb/m²

Detector Type: Flame Ionization Detector (F.I.D.)

Temperature Programming:
(i) initial 50°C (80°C for aromatic fractions)
(ii) 4°C/min up to 280°C
(iii) Isothermal at 280°C for 10-20 minutes

The relative abundance of individual molecular types was determined by comparing the integrated areas under respective peaks.

In Chookoo No.1, the distance between the two reservoir levels (i.e., "condensate" and crude oil) is only 8 meters and because of the high volatility of the condensate the analytical techniques were modified accordingly. The saturated fractions of both the untopped condensate and the untopped crude oil were separated by dissolving approximately 0.1gm of the material in 5ml of n-hexane and using elution column chromatography as for the +210°C fractions. Saturated fractions eluted were examined for the molecular types present, using gas chromatography with the same instrumental parameters.

5.2 Results

Bulk compositions of the fractions boiling above 210°C are shown in Table 5.2 and Figures 5.1 and 5.1A. The alkane distribution profiles of the total saturated fractions of the crude oils examined
Fig. 5.1  Bulk compositions of the crude oil (fraction boiling above 210°C)
BULK COMPOSITION OF CRUDE OIL

KEY
- LINEAR ALKANES
- BRANCHED AND CYCLIC ALKANES
- AROMATIC COMPOUNDS
- POLAR COMPOUNDS AND ASPHALTINES

Fig. 5.1A  Bulk composition of the crude oil - Naccowlah South, No.1 (fraction boiling above 210°C)
are given in Figures 5.2, 5.3, 5.4, 5.5, 5.6, and 5.6A. Figures 5.7, 5.8 and 5.8A are the histograms of the quantitative distribution of individual linear alkanes and regular isoprenoids in the saturated fractions. The bulk compositions indicate, all oils examined are low asphaltene, paraffinic-naphthenic type oils. The low polar and asphaltene content is typical of extensively migrated oils.

Table 5.2 - Composition of Crude Oils (Fraction boiling above 210°C)

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>% Saturate</th>
<th>% Aromatics</th>
<th>% Polar + Asphaltene</th>
<th>Linear Alkane Maximum</th>
<th>% C2₅+ Linear Alkanes</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>77.0</td>
<td>19.0</td>
<td>4.0</td>
<td>C1₄</td>
<td>6.9</td>
</tr>
<tr>
<td>2</td>
<td>78.0</td>
<td>19.0</td>
<td>3.0</td>
<td>C1₃</td>
<td>8.7</td>
</tr>
<tr>
<td>3</td>
<td>77.0</td>
<td>17.0</td>
<td>6.0</td>
<td>C1₅</td>
<td>8.1</td>
</tr>
<tr>
<td>4</td>
<td>78.0</td>
<td>19.0</td>
<td>3.0</td>
<td>C1₉</td>
<td>17.9</td>
</tr>
<tr>
<td>5</td>
<td>80.0</td>
<td>16.0</td>
<td>4.0</td>
<td>C1₉</td>
<td>15.6</td>
</tr>
<tr>
<td>6</td>
<td>77.2</td>
<td>18.8</td>
<td>4.0</td>
<td>C1₆</td>
<td>4.5</td>
</tr>
<tr>
<td>7</td>
<td>80.4</td>
<td>16.6</td>
<td>3.0</td>
<td>C1₉</td>
<td>26.5</td>
</tr>
<tr>
<td>9</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>9</td>
<td>82.5</td>
<td>13.9</td>
<td>3.6</td>
<td>C1₅, C1₉</td>
<td>19.5</td>
</tr>
<tr>
<td>10</td>
<td>82.0</td>
<td>13.0</td>
<td>5.0</td>
<td>C1₇</td>
<td>21.2</td>
</tr>
</tbody>
</table>

For Key, see Table 5.1.

5.2.1 N-alkane distribution

Hutton oils in Jackson No.1, Gunna No.1, Chookoo No.1, Naccoiwlah South No.1 and the Westbourne oil in Jackson No.1 are similar in having a relatively high content of waxy alkanes. These oils also have a linear alkane maximum at C1₉ (except Naccoiwlah South No.1 which has a linear alkane maximum at C1₇). The Hutton oil in Chookoo
Fig. 5.2 N-Alkane distribution profiles in the saturated fractions - Namur and Hutton Oils

NAMUR OIL
MERRIMELIA NO. 8

HUTTON OIL
MERRIMELIA NO. 8
Fig. 5.3  N-Alkane distribution profiles in the saturated fractions - Murta oils in Jackson No.1 and Gunna No.1 (fraction boiling above 210°C)
Fig. 5.4: N-Alkane distribution profiles in the saturated fractions - Westbourne and Hutton oils, Jackson No.1 (Fraction boiling above 210°C)
Fig. 5.5 N-Alkane distribution profiles in the saturated fractions - Hutton oils in Gunna No.1 and Chookoo No.1. (Fraction boiling above 210°C).
Fig. 5.6  N-Alkane distribution profiles in the saturated fractions - Hutton oil and condensate in Chookoo No.1 (fraction boiling above 210°C)
Fig. 5.6A - N-Alkane distribution profiles in the saturated fraction - Nacconlah South No. 1 (fraction boiling above 210°C).
Fig. 5.7  Histograms showing the quantitative distribution of alkanes in the saturated fraction of some Eromanga Basin oils.
Histograms showing the quantitative distribution of alkanes in the saturated fraction of some Eromanga Basin oils.
Fig. 5.8A Histograms showing the quantitative distribution of alkanes in the saturated fraction of the Hutton oil, Naccowlah South No.1.
No. 1 also has a secondary C\textsubscript{15} n-alkane maximum in addition to the C\textsubscript{19} peak. In contrast the Namur and Hutton oils in Merrimelia No. 8 and the Murta oils in Gunna No.1 and Jackson No.1 have a low waxy alkane content and the linear alkane maxima are in the range C\textsubscript{13} to C\textsubscript{15}. In all wells examined, the waxy oils generally occur in deeper reservoirs as compared to the reservoirs containing the low wax oils. Verdier et al. (1980) describe a similar evolutionary trend in the composition of oil in Handil Oil in East Kalimantan, Indonesia where heavy molecular weight n-alkanes are predominant in deep reservoir oils, compared to the light molecular weight n-alkane rich oils found in shallow reservoirs. They also concluded that these oils are derived from terrestrial organic matter dominated by vitrinite and that the source rocks have reached the levels of maturity of 0.4-0.7% $R_v$.

The alkane parameters derived are given in Table 5.3. The percentage pristane content is moderate in the saturated fractions of all oils, except the Murta oils where the percentage pristane content is high. The phytane content is consistently low in all samples. Like the pristane, the percentage abundance of the C\textsubscript{16} regular isoprenoid, T.M.T.D. (2, 6, 10 trimethyl tridecane) is high in the Murta oils, low in the Hutton oils in Jackson No. 1, Gunna No.1, Naccowlah South No. 1 and Chookoo No. 1 and the Namur and Murta oils from Merrimelia No. 8 have intermediate values.

5.2.2 Isoprenoid ratios

Pristane to phytane ratios are 1.0 in all oils indicating the source material is predominantly of terrestrial origin. The pristane to phytane ratio is highest in the Murta oils (both in Jackson No. 1 and Gunna No.1). This is probably due to the presence of less
Table 5.3 - Alkane Parameters

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>% Prist.</th>
<th>% Phyt.</th>
<th>% T.M.T.D.</th>
<th>Pr/Ph</th>
<th>T.M.T.D. Pr</th>
<th>Ph OEP</th>
<th>CPI C23-C30</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.65</td>
<td>0.47</td>
<td>1.43</td>
<td>3.48</td>
<td>0.87</td>
<td>0.32</td>
<td>0.10</td>
</tr>
<tr>
<td>2</td>
<td>1.22</td>
<td>0.38</td>
<td>1.17</td>
<td>3.21</td>
<td>0.95</td>
<td>0.33</td>
<td>0.11</td>
</tr>
<tr>
<td>3</td>
<td>2.52</td>
<td>0.38</td>
<td>1.60</td>
<td>6.65</td>
<td>0.63</td>
<td>0.41</td>
<td>0.07</td>
</tr>
<tr>
<td>4</td>
<td>1.33</td>
<td>0.48</td>
<td>0.61</td>
<td>2.75</td>
<td>0.45</td>
<td>0.26</td>
<td>0.08</td>
</tr>
<tr>
<td>5</td>
<td>1.33</td>
<td>0.34</td>
<td>0.67</td>
<td>3.94</td>
<td>0.50</td>
<td>0.25</td>
<td>0.05</td>
</tr>
<tr>
<td>6</td>
<td>3.69</td>
<td>0.54</td>
<td>1.93</td>
<td>6.81</td>
<td>0.52</td>
<td>0.42</td>
<td>0.07</td>
</tr>
<tr>
<td>7</td>
<td>1.59</td>
<td>0.41</td>
<td>0.59</td>
<td>3.87</td>
<td>0.37</td>
<td>0.28</td>
<td>0.06</td>
</tr>
<tr>
<td>8</td>
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<td>-</td>
<td>-</td>
</tr>
<tr>
<td>9</td>
<td>1.11</td>
<td>0.30</td>
<td>0.91</td>
<td>3.68</td>
<td>0.82</td>
<td>0.23</td>
<td>0.06</td>
</tr>
<tr>
<td>10</td>
<td>1.83</td>
<td>0.40</td>
<td>1.26</td>
<td>4.53</td>
<td>0.69</td>
<td>0.25</td>
<td>0.05</td>
</tr>
</tbody>
</table>

- No waxy alkanes in the range of C25-C33.

Reducing conditions during early diagenesis, where phytanic acid was mainly converted into pristane through decarboxylation rather than direct reduction to phytane. Powell and McKirdy (1976) concluded that the high wax, paraffine crude oils in the Cooper Basin have high pristane to phytane ratios. However the changes in the pristane to phytane ratios were attributed to the post accumulation maturation processes. The pristane to phytane ratio is low for the Merrimelia oils and the Westbourne oil in Jackson No.1. The Hutton oils in Jackson No.1, Gunna No.1 and Chookoo No.1 have intermediate pristane to phytane values. The T.M.T.D. to pristane ratio is high for the
Merrimelia oils and the Hutton oil in Chookoo No.1, compared to the rest of the oils. The pristane to n-C\textsubscript{17} ratios are comparatively high in the Murta oils, low in Hutton oils from the Jackson-Chookoo-Gunna area with the Namur and Hutton oils from the Merrimelia No.8 having intermediate properties.

Odd-even predominances (O.E.P.) of the n-alkanes were calculated using the formula given by Scanlan and Smith (1970). Similarly C.P.I. values were calculated using the method of Bray and Evans (1961). Both O.E.P. and C.P.I. values are low to moderate and, for terrestrial organic matter dominated sources, these parameters are interpreted as oil generated at moderate to high levels of thermal maturity. Vogler et al. (1981) used the O.E.P. values of the n-alkanes calculated over the range of C\textsubscript{14} to C\textsubscript{32} to separate crude oils generated from different sources. Correlation of crude oils using n-alkane distribution patterns and the O.E.P. values will be discussed in Chapter 7.

5.3 Discussion

As shown in Chapter 4, except for minor marine influence in the Murta Member, the organic matter contained in the Cooper/Eromanga Basin section examined is dominated by vitrinite and inertinite (Type III organic matter) or vitrinite and inertinite + exinite (Type II to Type III organic matter). Therefore the main factor governing the compositional changes in the crude oils reservoired at different stratigraphic levels should be the maximum level of thermal maturity and the duration of the exposure of organic matter to that level of thermal activity. However the compositional variations in the individual maceral groups, particularly the proportion of exinite
Fig. 5.9 Ternary diagram showing the composition of the crude oils from the Eromanga Basin reservoirs.
associated with predominantly Type III organic matter, may also have a significant role in determining the composition of hydrocarbons produced, as different macerals have the maximum hydrocarbon generation potential at different levels of thermal maturity.

The composition of hydrocarbons of oil samples is shown in a ternary diagram in Figure 5.9. It shows the Merrimelia oils have a relatively high branched and cyclic alkane content compared to the rest of the oils. The high alkane content in the Hutton oils in Gunna No.1, Naccowlah South No.1 and Chookoo No.1 is due to the presence of high percentages of waxy alkanes. A plot of the maturation parameters pristane to n-C_{17} and phytane to n-C_{18} for the crude oils is shown in Figure 5.10. Two features are distinct in this diagram.

i. All data plot within the field of humic type organic matter.

ii. A distinct evolutionary trend is observed from the Murta oils, through the Merrimelia oils to the Hutton and Westbourne oils in Jackson No.1 and Hutton oils in Gunna No.1, Naccowlah South No.1 and Chookoo No.1. Such a trend is more likely due to the variation in the levels of thermal maturity attained by parent organic matter.

Durand and Oudin (1979) proposed that vertical migration as the main cause for the accumulation of light oils in the upper stratigraphic levels in the Handil field in Indonesia. However the original data of Verdier et al. shows the pristane to n-C_{17} ratio decreases with depth. As pristane and n-C_{17} are chemically very closely associated, the changes in these ratios should be linked to the genetic evolution rather than migrational evolution of petroleum.

The composition of the n-alkanes and the calculated geochemical parameters suggest that the crude oils studied from the Mesozoic
Fig. 5.10 Relationship between pristane/n-C17 and phytane/n-C18 ratios in Eromanga Basin crude oils (modified after Connon and Cassau, 1980).
Table 5.4

Classification of Crude Oils into Genetic Groups

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Group I</th>
<th>Group II</th>
</tr>
</thead>
<tbody>
<tr>
<td>n-alkane maximum</td>
<td>C13 to C16</td>
<td>C-19*</td>
</tr>
<tr>
<td>% C23+ linear alkanes</td>
<td>&lt;10</td>
<td>&gt;10</td>
</tr>
<tr>
<td>C16 Isoprenoid (T.M.T.D.)</td>
<td>1.00&lt;</td>
<td>&gt;1.00</td>
</tr>
<tr>
<td>T.M.T.D./Pristane</td>
<td>&gt;0.60</td>
<td>&lt;0.60**</td>
</tr>
<tr>
<td>Pristane/Phytane</td>
<td>3.21-6.65</td>
<td>2.75-3.94</td>
</tr>
<tr>
<td>Pristane/n-C17</td>
<td>&gt;0.30</td>
<td>&lt;0.30</td>
</tr>
<tr>
<td>Pristane/n-C18</td>
<td>0.07-0.11</td>
<td>0.05-0.08</td>
</tr>
<tr>
<td>O.E.P. (at C23)</td>
<td>0.78-1.41</td>
<td>0.87-0.92</td>
</tr>
<tr>
<td>C.P.I.</td>
<td>1.13-1.30</td>
<td>0.88-1.24</td>
</tr>
</tbody>
</table>

e.g.

Merrimelia No.8
Namur oil
Hutton oil

Gunna No.1
Murta oil
Jackson No.1
Murta oil

Jackson No.1
Hutton oil

Gunna No.1
Hutton oil

Naccowlah South No.1 (Hutton oil)
Hutton oil

* Exception: Chookoo No.1 (Hutton oil) - also has a maximum of C15.
Naccowlah South No.1 (Hutton oil) - maximum at C17.

** Exception: Chookoo No.1 (Hutton oil) - T.M.T.D./Pristane = 0.82.
Naccowlah South No.1 (Hutton oil) - T.M.T.D./Pristane = 0.69.
Eromanga Basin fall into two main groups as shown in Table 5.4. Properties of these groups are given in Table 5.4. Within the Group I, Murta oils tend to be different from the Merrimelia oils in having relatively high pristane to phytane ratios and pristane to n-C\textsubscript{17} ratios, but low T.M.T.D. to pristane ratios. Hutton oil from Chookoo No.1 and Naccowlah South No.1 has properties similar to both Group I and II in having linear alkane maxima at both C\textsubscript{15}, C\textsubscript{17} and C\textsubscript{19}. However the similarities in the genetic parameters calculated using heavy molecular weight linear alkanes suggest that Chookoo and Naccowlah South No.1 oils are genetically similar to the Hutton oils in Jackson No.1, Gunna No.1 and to Westbourne oil in Jackson No.1. Figure 5.6 shows the alkane profiles of both the "condensate" and untopped Hutton oil in Chookoo No.1. The distance between two reservoir levels within the same formation is only 8 meters and it is unlikely that two oils have been reseroived separately. Although the saturated fraction of the condensate is more enriched in linear hydrocarbons less than C\textsubscript{9}, as compared to the saturated fraction of the crude oil, the following features suggest that the condensate probably originated from the crude oil by the process of diffusion-migration.

a) Minor amounts of heavy molecular weight linear alkanes (up to C\textsubscript{23}) are present in the condensate.

b) A similar naphthenic hump beyond C\textsubscript{23} occurs in both oil and condensate.

Perhaps one line of thinking is that the Hutton oil in Chookoo No.1 represent the typical Hutton oil in Jackson-Gunna area and the low lighter fraction in the latter may be due to subsequent migration (this is discussed further in Chapter 7).
Jackson No 1
Murta oil

Gunna No 1
Murta oil

Fig. 5.11 Branched and cyclic alkane distribution in the saturated fraction - Murta oils in Gunna No.1 and Jackson No.1.
Fig. 5.12 Branched and cyclic alkane distribution in the saturated fraction - Namur and Hutton oils, Merrimelia No. 8.
Fig. 5.13 Branched and cyclic alkane distribution in the saturated fraction - Hutton oils in Chookoo No.1 and Gunna No.1.
Fig. 5.14 Branched and cyclic alkane distribution in the saturated fraction - Westbourne and Hutton oils in Jackson No.1.
Jackson No 1
Murta oil

Gunna No 1
Murta oil

Distribution profile of the aromatic compounds - Murta oils in Jackson No.1 and Gunna No.1.
Fig. 5.16 Distribution profile of the aromatic compounds - Namur and Hutton oils, Merrimelia No. 8.
Fig. 5.17 Distribution profile of the aromatic compounds - Hutton oils in Chookoo No.1 and Jackson No.1.
Fig. 5.18 Distribution profile of the aromatic compounds - Westbourne oil in Jackson No.1 and Hutton oil in Gunna No.1.
The distribution profiles of branches and cyclic alkane fractions of the crude oils are shown in Figures 5.11, 5.12, 5.13 and 5.14. Peaks numerically marked are the peaks identified by mass spectral studies and the compositions are given in Table 5.5. A remarkable similarity in the distribution pattern of the heavy molecular weight branched and cyclic alkanes beyond phytane (peaks 9-15) is present in the Hutton oils in Jackson No.1, Chookoo No.1, Gunna No.1 and Westbourne oil in Jackson No.1. These peaks are distinctly different from the same peaks in Group I oils in that they have a high intensity. This evidence supports placing the oils into two genetic groups. These compounds are likely to have more genetic significance and were probably formed at a relatively advanced level of thermal maturity.

The distribution profiles of the aromatic compounds in the crude oils are given in Figures 5.15, 5.16, 5.17 and 5.18. The compositions of the numerically labelled main peaks are given in Table 5.6. The following empirical observations have been made in relation to the aromatic profiles.

i. Group II oils tend to have more peaks with retention temperatures 200°C when compared to the Group I oils. This is probably due to the increased aromatization of polycyclic naphthenes and naphthenoaromatics associated with increasing thermal maturity.

ii. The lack of peaks with low retention temperatures in the aromatic profiles of Gunna No.1 and Jackson No.1 is probably due to the removal of light molecular weight aromatics by water flushing and perhaps the aromatic profile of Chookoo No.1 could represent the original aromatic profiles of these Group II oils. Evidence of
Table 5.5

Some branched and cyclic alkanes identified from the saturated fraction of Hutton oil, Jackson No.1

<table>
<thead>
<tr>
<th>Peak No.</th>
<th>Empirical Formula</th>
<th>Structural Formula</th>
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<tbody>
<tr>
<td>1</td>
<td>C₁₁H₁₈</td>
<td>![Structural Formula 1]</td>
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<tr>
<td>2</td>
<td>C₁₂H₂₁</td>
<td>![Structural Formula 2]</td>
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</tr>
<tr>
<td>8</td>
<td>C₁₈H₃₈</td>
<td>![Structural Formula 8]</td>
</tr>
<tr>
<td>9</td>
<td>C₁₈H₃₆ + C₁₉H₄₀</td>
<td>![Structural Formula 9] + ![Structural Formula 10]</td>
</tr>
<tr>
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<td>![Structural Formula 11] + ![Structural Formula 12]</td>
</tr>
<tr>
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### Table 5.6

Some compounds identified from the aromatic fraction in the Murta oil, Jackson No. 1

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<tr>
<th>Peak No.</th>
<th>Empirical Formula</th>
<th>Structural Formula</th>
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</tr>
<tr>
<td>8</td>
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<td></td>
<td><img src="image11.png" alt="Structural Formula 11" /></td>
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<td>10</td>
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<td><img src="image12.png" alt="Structural Formula 12" /></td>
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Fig. 5.19 Relationship between the $R_{\text{v max}}$ of the reservoirs and the C$_{23+}$ linear alkane content (wax content) of some Eromanga Basin oils.
similar water washing of low molecular weight aromatics in crude 
oils from the Bolivar Coastal Fields of Venezuela have been 
discussed by Bockmeulen et al. (1983).

There are three possible ways by which the low molecular weight 
alkane dominated Group I oils may have formed:

i. the generation of large amounts of low molecular weight alkanes 
during the incipient phase of hydrocarbon generation.

ii. the cross stratigraphic movement of waxy crude oils and 
preferential accumulation of lighter oils in the upper 
stratigraphic levels; and

iii. the cracking of heavy molecular weight alkanes into lighter 
analogues during the advanced stages of thermal maturity.

Leythaeuser (1979) concluded that shorter chain alkanes are 
generated more readily at low energy levels and the longer chain 
alkanes seem to require an elevated kinetic energy to be released from 
the organic matter. Examples of fractionation of light oils as a 
consequence of cross stratigraphic movement of heavy oils are 
discussed by Illich et al. (1980).

Andreev et al. (1968) concluded that heavy molecular weight (both 
linear and branched) alkanes are predominant during the intermediate 
stages of generation and, at the initial and late stages of 
transformation, light molecular weight hydrocarbons are predominant.

Vitrinite reflectance data for the sections examined do not show 
the levels of maturity needed for the third mechanism. Also if such a 
mechanism is possible, then the genetic parameters should reflect the 
high degree of maturity of Group I oils. If the second mechanism is 
accepted, then there should be a marked difference in the polar and 
asphaltene content between two groups. Further, such a mechanism
should lead to the similarities in genetic parameters such as pristane to n-C17 and phytane to n-C18 between two groups. Therefore the mechanism favoured is the first mechanism. This mechanism agrees best with observed alkane parameters.

Figure 5.19 shows the relationship between the vitrinite reflectance of the reservoir horizons and the $C_{23}^+$ linear alkane content of the reservoired oil. The high degree of scatter may indicate the disequilibrium between the levels of maturity of oils and the reservoir horizons. Hedberg (1968) suggested that high wax oils may reflect the contribution of terrigenous organic matter (or of organic matter derived from aquatic organisms associated with waters of less than normal marine salinity). However it is probable that the maceral composition of the terrigenous organic matter as well as the age of organic matter (assuming the possibility of biochemical evolution of plant material associated with the organic evolution through geologic time) may also have a significant role in determining the waxy alkane content of the oil. Ronald et al. (1963) attributed the $C_{11}-C_{19}$ predominance common in crude oils from early Palaeozoic formation to the high proportion of saturated acids produced by plants and animals of that age. As discussed earlier the level of thermal maturation is likely to be significant in determining the waxy alkane content of the crude oils generated.

McKirdy (1979, in Barr et al., 1981) concluded that the crude oil reservoired in the Basal Hutton Formation in Poolawanna No.1 well in the Eromanga Basin is immature, waxy paraffinic oil which probably was sourced from Jurassic shales. Barr and Youngs (1981) expressed a similar view on the origin of Basal Jurassic oil in Cuttapirrie No.1.
However the organic petrological evidence suggest that the nearest best source horizons to the Hutton oil in Jackson No.1 lies in the Permian Gidgealpa group. In contrast in the Merrimelia Field the mature, best source horizons are located in the lower part of the Jurassic section. Geochemical data show that waxy oils of the Group II are more mature and originated in more deep seated (mature) sources. Source rock geochemistry (discussed in Chapter 6) indicates that incipient hydrocarbon generation commenced at vitrinite reflectance level of 0.7%. The peak values for pristane/n-C_{17} ratio correspond to the incipient phase of hydrocarbon generation phase. A sharp drop in the pristane/n-C_{17} ratio is observed during the main phase of generation. This is in agreement with the high pristane/n-C_{17} ratios of Group I oils and the low pristane/n-C_{17} ratios of the Group II oils which probably were generated at an elevated stage of thermal maturity.
A total of 25 samples including 6 core samples and 19 composite cutting samples were examined using standard organic geochemical techniques. Composite cuttings samples were obtained by mixing consecutive samples (usually 3 to 5) used in the organic petrological studies. Pooling of small samples was necessary in order to obtain adequately sized samples for Soxhlet extraction. All samples used in organic geochemical investigations had previously been examined for the type, amount and the level of thermal maturity of contained organic matter using organic petrological techniques.

6.1 Experimental

The finely ground cutting and core samples (90μm size) were extracted with a mixture of redistilled benzene and methanol (4:1 V/V) in a Soxhlet apparatus for 72 hours (modified after Ferguson, 1962). Typically 50gm of rock powder were used in the extraction, but for a few samples 15gm of sample was used due to the small size of the sample available. After the extraction, solvents were removed by rotary evaporation followed by evaporation under nitrogen. The extractable organic matter (EOM) was determined gravimetrically. The extracts were dissolved in 5ml of redistilled n-hexane and the asphaltenes were removed by filtering through a teflon filter film. The asphaltene free fractions were separated into saturated, aromatic and polar compounds using elution column chromatography on silica gel and activated alumina similar to the method used in crude oil analysis.
### Table 6.1 - Source Rock Geochemistry

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<th>E.O.M. (ppm) %</th>
<th>Sats. %</th>
<th>Arom. %</th>
<th>Polar %</th>
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* Core sample
The saturated (and for selected samples the aromatic, and branched plus cyclic) fractions were examined for the molecular types present using the same instrumental parameters described in Chapter 5.

Selected samples from the potential source rock intervals were also analysed for the total organic carbon content (T.O.C.), and the pyrolysis products using the Rock-Eval pyrolysis method (Barker, 1974; Claypool and Reed, 1976 and Espitalié et al., 1977).

6.2 Results and Discussion

Compositions of the extractable organic matter are given in Table 6.1. Linear alkane distribution profiles of the saturated fractions of the extracts are given in Figures 6.1 to 6.14. Quantitative distribution of the linear alkanes and the main isoprenoids in the saturated fractions are given in Figures 6.15 to 6.20. Table 6.2 gives the alkane parameters derived from the quantitative gas chromatographic data. Results of the Rock-Eval pyrolysis and the Total Organic Carbon (T.O.C.) are given in Table 6.3.

6.2.1 Total organic carbon

The total organic carbon (T.O.C.) content of most of the samples examined, except for the Nappamerri, Merrimelia and parts of the Westbourne Formation, is above the minimum critical limit accepted for hydrocarbon generation from clastic source rocks (0.5%, T.O.C.). High T.O.C. content in the Patchawarra, Toolachee and parts of the Basal Jurassic Formations is a combined effect of high d.o.m. and abundant coal lithologies present in the samples.

6.2.2 N-alkane distribution

In general, the Murta and Westbourne extracts contain few or no linear alkanes beyond C27, a situation analogous with the Murta oils
Table 6.2

Alkane Parameters
(source-rock extracts)

<table>
<thead>
<tr>
<th>Ext. %</th>
<th>T.M.T.D.</th>
<th>Pristane/Priseane/Phytane/n-C17</th>
<th>Pristeane/n-C18</th>
<th>O.E.P.</th>
<th>C.P.I.</th>
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+ Ratio not detectable owing to insignificant phytane content.
**Fig. 6.1**

N-alkane distribution profiles in the saturated fractions in the extracts - Murta Member, Jackson No.1.

**JACKSON NO.1**

**MURTA Mm.**

**1113 m.**

**RETENTION TIME (minutes)**

**1128-1137 m.**

**RETENTION TIME (minutes)**
Fig. 6.2 N-alkane distribution profiles in the saturated fractions in the extracts - Murta Member, Naccowlah No.1.
Fig. 6.3  N-alkane distribution profiles in the saturated fractions in the extracts - Murta Member, Packsaddle No.3 and Merrimelia No.8.
Fig. 6.4  
N-alkane distribution profiles in the saturated fractions in the extracts - 
Westbourne Formation - Merrimelia no.8 and Packsaddle No.3.
WESTBOURNE Fm.

JACKSON NO. 1

1336 m.

Fig. 6.5. N-alkane distribution profiles in the saturated fractions in the extracts of the Westbourne Formation, Jackson No. 1.
Fig. 6.6
N-alkane distribution profiles in the saturated fractions in the extracts - Birkhead Formation, Merrimelia No. 8.

BIRKHEAD Fm.

MERRIMELIA NO.8
1844-1856m.

FREQUENCY

RETENTION TIME (minutes)

C-11
C-13
C-15
C-17
C-19
C-21
C-23
C-25
C-27
C-29
Fig. 6.7
N-alkane distribution profiles in the saturated fractions in the extracts - Birkhead Formation, Packsaddle No. 3.

**BIRKHEAD Fm.**

**PACKSADDLE NO. 3**

1737-1753m.

1765-1777m.
Fig. 6.8 N-alkane distribution profiles in the saturated fractions in the extracts - Hutton Sandstone, Jackson No.1 and Packsaddle No.3.
Fig. 6.9 N-alkane distribution profiles in the saturated fractions in the extracts - basal Jurassic Unit, Naccowlah No.1 and Merrimelia No.8.
Fig. 6.10  N-alkane distribution profiles in the saturated fractions in the extracts—Nappamerri Formation, Merrimelia No.8 and Merrimelia No.5.
ROSENEATH Sh.

JACKSON NO. 1
1576-1588m.

Fig. 6.12 N-alkane distribution profile in the saturated fraction in the extract - Roseneath Shale, Jackson No.1.
Fig. 6.13 N-alkane distribution profiles in the saturated fractions in the extracts - Patchawarra Formation, Naccowlah No. 1, and Jackson No. 1.

**PATCHAWARRA Fm.**

**NACCOWLAH NO. 1**

2036-2045m.

**JACKSON NO. 1**

1606-1615m.
Fig. 6.14  N-alkane distribution profiles in the saturated fractions in the extracts - Merrimelia Formation, Packsaddle No.3 and Merrimelia No.8.
Fig. 6.15 Histograms showing the quantitative distribution of n-alkanes and isoprenoids in the saturated fractions of the extracts - Murta Member.
Fig. 6.16 Histograms showing the quantitative distribution of n-alkanes and isoprenoids in the saturated fractions of the extracts - Murta and Westbourne Formations.
Fig. 6.17 Histograms showing the quantitative distribution of n-alkanes and isoprenoids in the saturated fractions of the extracts - Birkhead Formation and Hutton Sandstone.
Fig. 6.18 Histograms showing the quantitative distribution of n-alkanes and isoprenoids in the saturated fractions of the extracts - Hutton Sandstone, basal Jurassic and Nappamerri Formations.
Fig. 6.19 Histograms showing the quantitative distribution of $n$-alkanes and isoprenoids in the saturated fractions of the extracts - Nappamerrri, Toolachee and Roseneath Shale.
Histograms showing the quantitative distribution of n-alkanes and isoprenoids in the saturated fractions of the extracts - Patchawarra and Merrimelia Formations.
in Jackson No.1 and Gunna No.1. In contrast, the Birkhead and Basal Jurassic extracts contain some linear alkanes beyond C27. The Toolachee and Patchawarra extracts in Jackson No.1 contain more waxy n-alkanes than the Murta and Westbourne extracts but the differences in wax content between these groups are small. These long chain n-alkanes are more likely to be the product of the decarboxylation of fatty acids rather than the result of polymerization of short chain hydrocarbons. The OEP values calculated are both low and variable. Philippi (1974) postulated that free radical mechanisms are more probable than the simple decarboxylation type reactions during the conversion of fatty acids in sediments to n-paraffins.

The linear alkane distribution pattern of the extracts is dissimilar to the generalized n-alkane distribution pattern for the land plant derived type III organic matter illustrated by Durand (1980). In all extracts the amount of n-alkanes beyond C25 is low except in the Nappamerri Formation extract in Merrimelia No.5 where anomalously high waxy alkane content is a result of possible contamination. Similar anomalously high waxy alkane in the source rock extracts due to the contamination of core box waxes have been described by Macqueen and Powell (1983). In all extracts few or no n-alkanes are found beyond C30, a property which is also observed in all crude oils studied from the Euromanga Basin. In contrast, high percentages of n-alkanes are found in the C13 to C20 ranges irrespective of the level of thermal maturity of the sediments. These features have been previously reported as being more typical of the extracts of type II organic matter derived from marine phytoplankton or from exinite rich source rocks (Tissot et al., 1974). These observations indicate the problems associated with the classification
of organic matter based on the composition of the extractable organic matter. Welte (1965) concluded that a petroleum and the extract of the related source rock do not have to be similar in their composition because petroleum corresponds with a certain phase in the development of the source rock. As discussed in Chapter 7, similar observations were found in correlating source rocks with crude oils in the study area.

Extracts from the marginally mature Murta Member contain a large amount of n-alkanes in the range of C_{13} to C_{20} with a very low content of n-alkanes beyond C_{25} (Figures 6.1, 6.2 and 6.3). This observation is interpreted as the early release of shorter side chains from the complex parent organic molecules, through reactions involving low activation energies. Allan and Douglas (1977) based upon the composition of the hydrocarbons extracted from sporinite and vitrinite concentrates, concluded that long chain n-alkanes are formed only at a slower rate up to a rank of 83.3% carbon (0.80% R_{vmax}). Between the rank of 83.3-83.9% carbon, the rate of generation of long chain n-alkanes increases remarkably and then declines. If this observation can be generalized to the dispersed organic matter, then the predominance of the shorter chain n-alkanes in most of the extracts (R_{vmax} below 0.80%) can be explained on similar grounds. A bimodal distribution of n-alkanes is observed in extracts from the underlying Westbourne Formation in Jackson No.1 and Packsaddle No.3 (Figures 6.4 and 6.5). Less pronounced bimodal tendency with a considerable content of n-alkanes with a carbon member greater than C_{25} is also observed in extracts from the Birkhead Formation in Packsaddle No.3 (Figures 6.6 and 6.7). Hutton Sandstone in Jackson No.1 and in extracts from the Basal Jurassic unit in Merrimelia No.8 (Figures 6.8 and 6.9). This is interpreted as the succeeding phase where heavy
molecular weight n-alkanes are generated as a result of reactions involving higher activation energies, in addition to the alkanes with shorter carbon chains. The bimodal tendency observed in the n-alkane distribution in the extract from the Merrimelia Formation in Packsaddle No.3 is probably due to the presence of cavings, a prominent caving population being noted during the organic petrological studies.

The skewed distribution with C₁₃ to C₂₀ range predominance is found in extracts from the Toolachee Formation in Jackson No.1 and in extract from the Patchawarra Formation in Jackson No.1 and Naccowlah No.1 (less prominent). This third phase is interpreted here as the thermal disproportionation of the majority of long chained linear alkanes into shorter chain, more stable alkanes. However the extracts from the same formation at different locations can show different compositional distributions. These differences are probably due to one or more of the following factors:

i) level of thermal maturity attained by the same formation at different localities;

ii) local variations in the composition of organic matter;

iii) extent of synsedimentary and post-sedimentary biodegradation of the organic matter;

iv) the extent to which hydrocarbons have migrated out since their generation; and

v) experimental difficulties such as the matrix effects on the extractability and preferential adsorption effects of hydrocarbons on the mineral matter.

The Westbourne Formation extract in Merrimelia No.8, unlike other Westbourne extracts, does not show any bimodal tendency. Similarly
both Toolachee and Patchawarra extracts in Naccowlah No.1 contains little or no n-alkanes beyond C25, when compared with the Toolachee and Patchawarra extracts in Jackson No.1. This difference is most likely due to the compositional early biodegradation characteristics of the organic matter rather than a maturation effect.

6.2.3 Alkane parameters

The geochemical parameters of genetic significance are compared in Figures 6.21, 6.22, 6.23 and 6.24, directly with the vitrinite reflectance instead of the maximum depth of burial to eliminate the uncertainties involved in estimating the maximum depth of burial. Figure 6.21 is a plot of vitrinite reflectance against the pristane to phytane ratio of the extract. The data show a high degree of scatter with no relationship being apparent between the variables. This is probably due to the dependence of the pristane/phytane ratio on several variables other than the thermal maturity, such as the composition of the parent organic matter and the effective redox environment during early diagenesis. The relationship between total hydrocarbons (saturates plus aromatics) in the extracts and the vitrinite reflectance is shown in Figure 6.22. The number of data points is not adequate to formulate a firm distribution profile, but is sufficient to indicate the inception of hydrocarbon generation at vitrinite reflectance of 0.40%, with more prolific generation around 0.50-0.70% \( R_v \). This phase of generation probably corresponds to the release of short chain hydrocarbons and less complex aromatics through disproportionation reactions involving low activation energies. Tissot and Espitalié (1975) concluded that degradation of land plant derived type III organic matter occurs at much lower activation energies when compared with algal derived type I and marine sourced,
type II organic matter. Relationship between the saturates/aromatics ratio and the vitrinite reflectance of the extracts is shown in Figure 6.23. The distribution profile shows a tendency to peak around a vitrinite reflectance of 0.50%. This could be interpreted as the early generation of light molecular weight alkanes at a higher rate than the aromatics, which probably requires a higher activation energy to leave the parent organic structures.

Figure 6.24 shows the relationship between the maturation parameters, pristane/n-C_{17} and the vitrinite reflectance of the samples. High values of pristane/n-C_{17} ratios occur around 0.5-0.70% \( R_v \text{max} \). The high pristane/n-C_{17} ratio is indicative of the early phase of hydrocarbon generation involving the release of lighter linear alkanes and branched and cyclic alkanes (including isoprenoids), because the branched chain compounds probably need less activation energy to undergo elimination type reactions, compared with their straight chain analogues owing to the reduction of the steric hindrance around parent organic complexes. The general decrease of this ratio with the increasing vitrinite reflectance is interpreted as the dilution effect caused by the generation of medium to high molecular weight n-alkanes with progressive thermal maturity. A similar argument could be extended to the phytane/n-C_{18} ratio, but phytane is present in such low quantities that the phytane/n-C_{18} ratio may not be a robust measure of generation characteristics.

As pristane and the n-C_{17} linear alkane are similar in their physico-chemical properties, it is unlikely that this ratio is significantly altered during migration. Crude oil formed during the early phase of hydrocarbon generation should have high pristane/n-C_{17} ratios and the ratio should decrease with an increase in thermal maturity of the organic matter. This type of trend can be interpreted
Fig. 6.21 Relationship between the vitrinite reflectance and the pristane to phytane ratios in the extracts.
Fig. 6.22 Relationship between the vitrinite reflectance and the hydrocarbon contents in the extracts.
Fig. 6.23 Relationship between the vitrinite reflectance and the saturate to aromatic ratios in the extracts.
Fig. 6.24 Relationship between the vitrinite reflectance and the pristane to $n$-C$_{17}$ ratio in the extracts.
### Table 6.3

Rock-Eval Pyrolysis Data

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<th>S2</th>
<th>S3</th>
<th>S1 + S2</th>
<th>S1 + S2</th>
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<td>0.21</td>
<td>0.24</td>
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<td>2.27</td>
<td>0.79</td>
<td>2.89</td>
<td>0.21</td>
<td>0.21</td>
<td>0.24</td>
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<td>0.21</td>
<td>0.21</td>
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<td>0.24</td>
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<tr>
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<td>461</td>
<td>0.62</td>
<td>2.27</td>
<td>0.79</td>
<td>2.89</td>
<td>0.21</td>
<td>0.21</td>
<td>0.24</td>
<td>158</td>
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<tr>
<td>25</td>
<td>0.34</td>
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<td>2.27</td>
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<td>0.21</td>
<td>0.21</td>
<td>0.24</td>
<td>158</td>
<td>55</td>
</tr>
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</table>
as being present in the crude oils studied from the Eromanga Basin. The Murta oils have high pristane/n-C_{17} ratios and waxy Hutton and Westbourne oils in the Jackson area have low pristane/n-C_{17} ratios with crude oils from Merrimelia No.8 having intermediate ratios (Table 5.4).

6.2.4 Rock-Eval pyrolysis

The use of pyrolysis methods in source rock evaluation have been described by several authors, e.g., Barker (1974), Claypool and Reed (1976) and Dembicki et al. (1983). Page and Clarence (1980) assumed that the temperature range of 435°C-450°C for T max (maximum temperature corresponding to the peak release of hydrocarbons by the thermal degradation of organic matter during pyrolysis) indicated the zone of oil generation. Rock-Eval pyrolysis data given in Table 6.3 show that most of the samples examined lie within this range and the correlation between the T max and the vitrinite reflectance is fair (Figure 6.25). A plot of two maturation parameters, vitrinite reflectance vs. EOM/TOC ratio is given in Figure 6.26. This relationship reveals that prolific hydrocarbon has occurred at vitrinite reflectance values of 0.50 to 0.60%. This range is lower than that for most. Their observation is contrary to most conventionally accepted models, but is consistent with the rest of the geochemical results. However the correlation between the vitrinite reflectance and the transformation ratio ($S_1/S_1 + S_2$) is relatively weak (Figure 6.27). Similarly, typing of organic matter using Hydrogen and Oxygen indices on a van Krevalan diagram (Figure 6.28) shows a broader scatter between Type II and Type III organic matter fields, although organic petrological studies reveal that the organic matter examined consists predominantly of land plant derived phytoclasts.
Fig. 6.25 Relationship between the vitrinite reflectance and the Tmax values of the source rock samples.
Fig. 6.26 Relationship between the vitrinite reflectance and the E.O.M. to T.O.C. ratios of the source rock samples.
which can be assigned to Type III organic matter. Katz (1981) concluded that the S1 peak, and hence the oxygen index is influenced by the mineral matrix, through the addition of inorganic carbon dioxide. Similarly Espitalié et al (1980), Horsefield et al. (1980), and Katz (1981) inferred that the S-2 peak is influenced by the mineral matrix, mainly due to the adsorption of heavy molecular weight hydrocarbons by clay molecules. Vitrinite reflectance is least affected by the mineral matrix and the poor correlation between the pyrolysis data and the vitrinite reflectance is probably due to matrix effects. It is unlikely that the T max values are greatly influenced by the mineral matrix and the fair correlation between the vitrinite reflectance values and the T max values may confirm these interpretations.

6.2.5 Aromatic hydrocarbons

The distribution profiles of the aromatic fractions of selected source horizons are given in the Figures 6.29 to 6.33. The aromatic profiles are very similar at all depths in having a high proportion of mono and binuclear aromatics and substituted derivatives. Similar observations have been made by Albrecht et al (1976) in Douala Basin in Cameroon. Radke et al. (1982) have proposed a methyl phenantherene index (MPI) based on the amount of phenantherene and its four methyl isomers in the aromatic fraction as a reliable guide to the thermal maturity of organic matter in the sediments.

7.2.7 Branched plus cyclic alkanes

Figures 6.34 to 6.36 show the distribution of the branched and cyclic alkane distribution for some selected source horizons. No clear distinction has been observed in the amount of branched and
Fig. 6.27 Relationship between the vitrinite reflectance and the transformation ratios of the source rock samples.
Fig. 6.28 Typing of organic matter using Oxygen and Hydrogen indices (After Espitalié et al., 1977).
Fig. 6.29  Distribution profiles of the aromatic compounds in the extracts - Murta Member.
BIRKHEAD Fm.

MERRIMELIA NO.8
1844-1856m.

Fig. 6.30 Distribution profiles of the aromatic compounds in the extracts - Birkhead Formation.
Fig. 6.31 Distribution profiles of the aromatic compounds in the extracts - basal Jurassic unit.
Fig. 6.32 Distribution profiles of the aromatic compounds in the extracts - Toolachee Formation.
Fig. 6.33 Distribution profiles of the aromatic compounds in the extracts - Patchawarra Formation.
Fig. 6.34 Distribution profiles of the branched and cyclic alkanes in the saturated fractions in the extracts - Westbourne and Birkhead Formations.
Fig. 6.35 Distribution profiles of the branched and cyclic alkanes in the saturated fractions in the extracts - basal Jurassic unit and Toolachee Formation.
Fig. 6.36 Distribution profiles of the branched and cyclic alkanes in the saturated fractions in the extracts - Patchawarra Formation.
<table>
<thead>
<tr>
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<th>Merri. No. 5</th>
<th>Packsad. No. 3</th>
<th>Jack. No. 1</th>
<th>Naccow. No. 1</th>
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<td>A</td>
<td>B</td>
<td>A</td>
<td>B</td>
<td>A</td>
</tr>
<tr>
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<td>Patchawarra</td>
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<td>Merrimelia</td>
<td></td>
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Table 6.4 Comparison of the source potentials of different stratigraphic units using organic petrological and geochemical methods.

<table>
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<th>Symbol</th>
<th>Org.Petrology (Limits OMAF Units)</th>
<th>Org.Geochem. Hydrocarbons ppm</th>
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<tr>
<td>V. good &gt;40</td>
<td></td>
<td>&gt;2250</td>
</tr>
<tr>
<td>Good 20-40</td>
<td></td>
<td>1500-2250</td>
</tr>
<tr>
<td>Fair 15-20</td>
<td></td>
<td>750-1500</td>
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<tr>
<td>Poor &lt;15</td>
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<td>&lt;750</td>
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</table>
cyclic alkanes with retention temperatures greater than pristane between source rock extracts with different levels of maturity, except in the Westbourne Formation extract. This leads to the conclusion that the characteristically high proportion of these compounds observed in the Hutton and Westbourne oils in the Jackson-Gunna area as compared to the Merrimelia oils could partly be due to post accumulation maturation processes.

As all the samples examined appear to be mature enough to generate hydrocarbons, the amount of hydrocarbon in grams per kilogram of source rock can be used as an approximate guide to determine the relative source potential of different stratigraphic units. The following arbitrary limits were set for the purpose of comparison.

<table>
<thead>
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<th>Limit</th>
<th>Source Rating</th>
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<tr>
<td>750 ppm</td>
<td>Poor</td>
</tr>
<tr>
<td>750-1500 ppm</td>
<td>Fair</td>
</tr>
<tr>
<td>1500-2250 ppm</td>
<td>Good</td>
</tr>
<tr>
<td>2250 ppm</td>
<td>Very good</td>
</tr>
</tbody>
</table>

Geochemical source ratings attributed to different stratigraphic units are compared with the source rating established by organic petrology in Table 6.4. Source ratings by two methods are generally compatible except for the Toolachee and Roseneath Shale Formations where the organic geochemical rating is much lower than the source rating by organic petrology methods. Migration of generated hydrocarbon is one possible reason for this discrepancy and a low specific generation capacity for migrateable hydrocarbons from coal-dominated sequences is a further possible cause. The low geochemical source rating for the Murta Member compared to its organic matter abundance is likely due to the lack of adequate maturity for the prolific generation of hydrocarbons.
CHAPTER 7

CORRELATIONS AND DISCUSSION

Introduction

Correlations considered in this study are of four types:

i. Correlations between the petrological and geochemical data used in source rock evaluation.

ii. Correlation between crude oils to elucidate any genetic relationships within the different types of oils.

iii. Correlation between the geochemical parameters from different locations within the same stratigraphic units to examine the extent of variation with stratigraphic units and, from this, assess the limitations of the applicability of the present data to other areas.

iv. Correlation between the geochemical properties of crude oils and the equivalent property of source rock extracts as a means of evaluating genetic relationships between the crude oils and the potential source rocks.

7.1 Maceral/Extract Correlations

Case histories of the comparison of organic petrological and organic geochemical methods used in source rock evaluation are few in literature, e.g., Kantsler et al. (1983), Smyth and Saxby (1981). In most source rock studies, the emphasis is placed mainly on either petrological or geochemical methods. A comparison of the organic geochemical data and the semiquantitative organic petrological data
(O.M.A.F. values) for the samples examined from five wells studied is shown in Figures 7.1 to 7.5. (Visual comparisons were made as there was not enough data for rigorous statistical analysis.) The correlation between the volumetric abundance of the organic matter and the amount of extractable organic matter in the samples is generally fair to good. The relatively high amount of extractable organic matter compared to the volumetric abundance of organic matter in the Murta Member samples in Jackson No.1 may be due to two causes: (i) contamination with the pooled hydrocarbons from the Murta Reservoir; and (ii) due to the presence of finely disseminated organic matter which was not detected during petrological examinations.

The relatively low extractable organic matter content of the Murta Member in Merrimelia No.8 (Figure 7.3) compared to the volumetric abundance of the organic matter is probably due to the low level of thermal maturity (0.48% \( R_{\text{ym}} \)). The low extractable organic matter content in comparison to the high volumetric abundance of organic matter in the Toolachee Formation in Jackson No.1 is associated with the presence of large amounts of shaly coal, an effect possibly accentuated by the abundance of inertinite. By contrast coal-rich horizons such as the Patchawarra Formation in Jackson No.1 and Naccowlah No.1 and the lower Jurassic units in the Merrimelia No.8 show a high solvent extractable organic matter content with a large amount of asphaltene material being present in the extract.
Fig. 7.1 Comparison of the volumetric abundance of organic matter and the solvent extractable organic matter in source rocks - Jackson No.1.
Comparison of the volumetric abundance of organic matter in source rocks - N ACCOWLAH No. 1.

Core sample

Toolachie fm. (1865m.)

0.92

15662

EOM (ppm.)

% Abundance
Fig. 7.3 Comparison of the volumetric abundance of organic matter and the solvent extractable organic matter in source rocks - Merrimelia No.8.
MERRIMELIA NO. 8

Sample No

15440
15429
15430
15431
15432
15433
15434
15435
15436
15437
15438
15439

OMAF (> 2% Level of abundance)
Fig. 7.4 Comparison of the volumetric abundance of organic matter and the solvent extractable organic matter in source rocks - Merrimelia No.5.
Fig. 7.5 Comparison of the volumetric abundance of organic matter and the solvent extractable organic matter in source rocks - Packsaddle No. 3.
7.2 Oil Correlation

Geochemical correlations of crude oils have been attempted by several workers, e.g., Jones and Smith (1965), Williams (1974), Dow (1974), Koons et al. (1974) and Voglar et al. (1980). Oil-oil correlations were made in order to:

(i) identify various types of families of crude oils present in the sedimentary basin; and
(ii) infer the probable origin of the crude oil families.

Early oil correlations were based on the comparison of simple physical properties such as the API gravity, viscosity, sulphur content and distillation boiling ranges, e.g., Williams (1974), Barba (1967), McKirdy and Powell (1973).

The correlation index introduced by Smith (1940) was a major development in oil correlation technology. Williams (1974) concluded that these properties provide only gross distinction of genetic oil types and are significantly affected by migration, maturation and degradation. The methods used in oil-oil, and oil-source rock correlations are summarized by Barker (1979).

Most workers prefer a multi-parameter approach in correlating crude oils. Parameters used include:

i. n-alkane distribution in the saturated hydrocarbon fraction;
ii. isoprenoid ratios;
iii. isoprenoid to n-alkane ratios;
iv. carbon isotope ratios, e.g., Silverman (1967), Williams (1974) and Feux (1977);
v. light hydrocarbon ratios such as cyclopentane to normal paraffins, e.g., Williams (1974), Erdman and Morris (1974);
vi. non-hydrocarbon compounds like thiophene e.g., Tissot et al. (1974), Deroo (1976);  

vii. C_{27+} cyclic alkanes, e.g., Philippi (1965), Deroo et al. (1975);  

viii. optical rotation measurements e.g., Williams (1974); and  

ix. sulphur content, e.g., Barbat (1967) and Williams (1974).  

x. nickel and vanadium contents, e.g., Al-Shahristani et al. (1972).  

However, due to the limitations of facilities and time available only the first three of the correlation parameters listed above were used in this study. \( C_{15+} \) n-alkane distribution in the saturated fraction in crude oils is used as a correlation parameter by several workers, e.g., Martin et al. (1963), Williams (1974), Deroo et al. (1975). Figure 7.6 shows the \( C_{13+} \) linear alkane distribution profiles of the saturated fractions in crude oil samples from nine reservoirs located in the Eromanga Basin. The presence of three different families or suites of crude oils is evident in this diagram. As will be explained below these three suites can be considered as two groups with one group divided into two sub-groups.  

**Group I oils**: N-alkane peak around \( C_{15} \) with very little n-alkanes beyond \( C_{23} \) (e.g., Murta oils in Jackson No.1, Gunna No.1 and Namur and Hutton oils in Merrimelia No.8).  

**Group II oils**: subdivided into two sub-groups, i.e.,  

**Group IIa oils**: n-alkane mode at \( C_{19} \) with a substantial amount of n-alkanes beyond \( C_{23} \) (e.g., Hutton oils in Jackson No.1, Gunna No.1 and the Westbourne oil in Jackson No.1).  

**Group IIb oils**: n-alkane mode at \( C_{15}-C_{17} \) with a substantial amount of n-alkanes beyond \( C_{23} \) (e.g., Hutton oils in Chookoo No.1 and Naccowlah South No.1).
Fig. 7.6  $C_{13+}$ n-alkane distribution profiles of the crude oils.
Long chain isoprenoid hydrocarbons like pristane and phytane are widely used in oil correlations, e.g., Powell and McKirdy (1975), Welte (1966), Sutton (1977), Lijmbach (1975), and Welte et al. (1975) preferred to use the ratios of isoprenoids to n-alkanes as parameters of genetic significance particularly when correlating crude oil with source rocks.

The parameters pristane to n-C_{17} ratios, phytane to n-C_{18} ratios, \%C_{16} regular isoprenoid content and the pristane to phytane ratios have already been discussed in Chapter 5 (Tables 5.3 and 5.4, Chapter 5). These parameters show that the group IIa and group IIb oils are very similar and perhaps represent two subgroups within one genetic group of oils. One explanation for the difference in these groups is that both group IIa and group IIb oils originally had the composition of group IIb oils (e.g., Hutton oils in Chookoo No.1 and Naccowlah South No.1) but the group IIa oils have evolved from the group IIb type of oils through the loss of light molecular weight n-alkanes due to the migration and/or post accumulation evolution within the reservoir. However if such a hypothesis is valid, then there is a likelihood of finding condensate type deposits in nearby stratigraphic traps, a phenomenon yet to be found. The genetic similarities between the "condensate" and group IIb type oil in Chookoo No.1 have already been discussed in Chapter 5.

Erdman and Morris (1974) used a plot of odd-even predominance of n-alkanes as a function of carbon number to separate crude oils according to their origin. A plot of odd-even predominance (OEP) against the carbon number for group I and group II (combination of group IIa and group IIb) is shown in Figures 7.7 and 7.8. Although the magnitudes of the OEP values for the ten groups are different both
show OEP value maxima and minima at similar carbon numbers. This observation could be interpreted as indicating that the precursors of the linear alkanes in the crude oils had similar compositions. Erdman and Morris concluded that the carbon numbers at which the OEP maxima and minima fall are indicative of source characteristics, whereas the amplitudes or size of the departure of the OEP values from unity is indicative (inversely) of the yield of oil from the source rock. The organic petrological studies show that the stratigraphic sequences studied in the Cooper/Eromanga Basin sequence contain predominantly terrestrially derived organic matter. The generation of two different groups of crude oils (i.e., group I and group II oils) from such organic matter is likely to be primarily a function of the maximum levels of thermal maturity attained by the phytoclasts at different localities although significant type differences are present within the organic matter (Cook, 1982).

The group I oils may have originated by several possible mechanisms. These are discussed in detail in Chapter 5.

7.3 Intrastratigraphic correlation

Parameters used in oil-oil correlation have also been used by many workers to correlate the crude oils with source rock extracts, e.g., Williams (1974), Welte et al. (1975), Combaz and de Matharel (1978). Oil-source rock correlations are more difficult than oil-oil correlations because of the problems involved both in sampling and in interpreting data. These problems are summarized by Hunt (1979).

The C13+ n-alkane distribution profiles of the saturated fractions in source rock extracts are given in Figures 7.9 to 7.16. For a given source horizon, the degree of consistency in the alkane parameters is high for the basal Jurassic and Patchawarra Formation,
Fig. 7.7 A plot of odd even predominance vs the carbon number - group I oils.
Fig. 7.8 A plot of odd even predominance vs the carbon number - group II oils.
Fig. 7.9  Intrastratigraphic correlation of the $C_{13+}$ n-alkane distribution profiles - Murta Member. (Symbols as in Fig. 7.6)
fair in the Birkhead and Hutton Sandstone Formations, and low in Murta, Westbourne and Toolachee Formations. Poor correlation between the n-alkane distribution profiles from different parts of the same formation can be attributed to one or more of the following reasons:

i. changes in the composition of organic matter in different parts of the formation;

ii. changes in the levels of maturity attained;

iii. presence of cavings and other contaminants in the sample; or

iv. contamination of the possible source rocks by migrated oils. The Murta Member and the Toolachee Formation lie beneath regional seals and are presumably susceptible to contamination by migrated hydrocarbons and any migrated hydrocarbons are more likely to have had a diverse source.

7.4 Oil-source rock correlations

In Figures 7.17 to 7.20, the n-alkane distribution profiles of the saturated fraction in Merrimelia No.8 oils are compared with the n-alkane distribution of the extracts from four potential source horizons from the Merrimelia field. The correlations of oil as possible source rock extracts are good for the extracts, from the Murta Member, fair for the extracts from Birkhead and basal Jurassic Formation and poor for the extract from the Westbourne Formation. The correlation of the n-alkane distribution profiles of Murta oils in Jackson No.1 and Gunna No.1 with the n-alkane distribution profiles of the extracts from Murta and Westbourne Formation is shown in Figure 7.21. Correlation is generally fair for the Murta extracts and poor for the Westbourne extract. Similar comparisons of the group IIa and group IIb oils and the extracts from the basal Jurassic and Toolachee Formations are given in Figure 7.22. Figure 7.23 is the correlation of Group II oils with the Roseneath Shale and Patchawarra Formation
Fig. 7.10 Intrastratigraphic correlation of the C$_{13+}$ n-alkane distribution profiles - Westbourne Formation. (Symbols as in Fig. 7.6)
Fig. 7.11  Intrastatigraphic correlation of the C_{13} n-alkane distribution profiles - Birkhead Formation. (Symbols as in Fig. 7.6)
Fig. 7.12 Intrastratigraphic correlation of the C_{13}, n-alkane distribution profiles - Hutton Sandstone. (Symbols as in Fig. 7.6)
Fig. 7.13 Intrastratigraphic correlation of the C_{13+} n-alkane distribution profiles - Basal Jurassic. (Symbols as in Fig. 7.6)
Fig. 7.14 Intrastratigraphic correlation of the $C_{13}$-$n$-alkane distribution profiles - Toolachee Formation. (Symbols as in Fig. 7.6)
Fig. 7.15 Intrastratigraphic correlation of the C_{13} n-alkane distribution profiles - Patchawarra Formation. (Symbols as in Fig. 7.6)
Fig. 7.16  Intrastratigraphic correlation of the C_{13} n-alkane distribution profiles - Merrimelia Formation. (Symbols as in Fig. 7.6)
Table 7.1 Comparison of main correlation parameters

<table>
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<th>Formation</th>
<th>N</th>
<th>T.M.T.D./Pr</th>
<th>Pristane/Phyt</th>
<th>Pristane/N-C17</th>
<th>Phytane n-C18</th>
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<td>5.15</td>
<td>0.62</td>
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<td></td>
<td></td>
<td>(0.53-0.93)</td>
<td>(4.27-6.81)</td>
<td>(0.35-1.26)</td>
<td>(0.07-0.19)</td>
</tr>
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<td>Westbourne</td>
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<td>0.62</td>
<td>5.53</td>
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<td>(2.53-8.69)</td>
<td>(0.11-0.65)</td>
<td>(0.02-0.16)</td>
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<td>4.79</td>
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<td>(0.41-0.46)</td>
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<td>(0.41-0.48)</td>
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<td>(7.2-7.3)</td>
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<td>(0.40-0.71)</td>
<td>(0.04-0.10)</td>
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<tr>
<td>Group I oil</td>
<td>4</td>
<td>0.74</td>
<td>5.03</td>
<td>0.37</td>
<td>0.08</td>
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<tr>
<td></td>
<td></td>
<td>(0.52-0.95)</td>
<td>(3.21-6.81)</td>
<td>(0.32-0.42)</td>
<td>(0.07-0.11)</td>
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<tr>
<td>Group IIa oil</td>
<td>3</td>
<td>0.44</td>
<td>3.52</td>
<td>0.26</td>
<td>0.06</td>
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<tr>
<td></td>
<td></td>
<td>(0.37-0.50)</td>
<td>(2.75-3.94)</td>
<td>(0.25-0.28)</td>
<td>(0.05-0.08)</td>
</tr>
<tr>
<td>Group IIb oil</td>
<td>2</td>
<td>0.75</td>
<td>4.10</td>
<td>0.24</td>
<td>0.06</td>
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<tr>
<td></td>
<td></td>
<td>(0.69-0.82)</td>
<td>(3.68-4.53)</td>
<td>(0.23-0.25)</td>
<td>(0.05-0.06)</td>
</tr>
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</table>

N = No of analyses
Value in brackets show the range.
Fig. 7.17  Correlation of the C₁₃₆ n-alkane distribution profiles of the crude oils from the Merrimelia No.8 with the Murta extracts (Symbols as for Fig. 7.6, broken lines show extracts).
Fig. 7.18 Correlation of the C₁₃⁺ n-alkane distribution profiles of the crude oils from the Merrimelia No.8 with the Westbourne extract (Symbols as for Fig. 7.6, broken lines show extracts).
Fig. 7.19 Correlation of the C_{13+} n-alkane distribution profiles of the crude oils from the Merrimelia No.8 with the Birkhead extracts (Symbols as for Fig. 7.6, broken lines show extracts).
Fig. 7.20 Correlation of the C_{13+} n-alkane distribution profiles of the crude oils from the Merrimelia No.8 with the basal Jurassic extract (Symbols as for Fig. 7.6, broken lines show extracts).
Correlation of the C$_{13}$ n-alkane distribution profiles of the crude oils from the Murta reservoir in Jackson area with the Murta and Westbourne extracts (Symbols as for Fig. 7.6, broken lines show the extract).
Fig. 7.22 Correlation of the C_{13}, n-alkane distribution profiles of the group II crude oils with the Toolachee and basal Jurassic extracts (Symbols as for Fig. 7.6, broken lines show the extract).
Fig. 7.23 Correlation of the C_{13} n-alkane distribution profiles of the group II crude oils with the Patchawarra and Roseneath Shale extracts (Symbols as for Fig. 7.6, broken lines show the extract).
Table 7.2 - Comparison of source rating of the stratigraphic units

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<td>Murta</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>xxx</td>
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<td>-</td>
<td>-</td>
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<td>-</td>
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<td>Westbourne</td>
<td>x</td>
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<td>-</td>
<td>-</td>
<td>-</td>
<td>x</td>
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<tr>
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<td>-</td>
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<td>-</td>
<td>-</td>
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<td>xxx</td>
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<td>x</td>
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<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
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<td>Basal Jurassic</td>
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<td>x</td>
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<td>-</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
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<td>-</td>
</tr>
<tr>
<td>Toolachee</td>
<td>xxxx</td>
<td>xx</td>
<td>xxxx</td>
<td>x</td>
<td>-</td>
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<tr>
<td>Roseneath</td>
<td>xxxx</td>
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<td>-</td>
<td>-</td>
<td>xxx</td>
<td>xxx</td>
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<td>-</td>
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<tr>
<td>Patchawarra</td>
<td>xxxx</td>
<td>xxxx</td>
<td>xxx</td>
<td>xxx</td>
<td>-</td>
<td>-</td>
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<td>-</td>
<td>x</td>
<td>x</td>
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<tr>
<td>Poor</td>
<td>x</td>
<td>15 units OMAF</td>
<td>&lt;750 ppm EOM</td>
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<td>Fair</td>
<td>xx</td>
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<td>xxx</td>
<td>20-40 units OMAF</td>
<td>1500-2250 ppm EOM</td>
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<td>Very Good</td>
<td>xxxx</td>
<td>40 units OMAF</td>
<td>&gt;2250 ppm EOM</td>
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<tr>
<td>Not available</td>
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</table>

* Unclassified Gidgealpa Group
extracts from the Jackson-Gunna area. The correlation between the high wax group IIa oils and the source rock extracts is poor. However the correlations between the group IIb oils and most of the lower Jurassic and Patchawarra Formation extracts are generally good to fair.

7.5 Discussion

Other correlating parameters, T.M.T.D. to pristane ratios, pristane to phytane ratios, pristane to n-C17 ratios and phytane to n-C18 ratios for both crude oils and source rock extracts are compared in Table 7.2 and Figure 7.24. The T.M.T.D. (C16 regular isoprenoid) to pristane ratio shows a scatter down the stratigraphic sequence and hence appears to be unsuitable for oil-source rock correlation. Similarly pristane to phytane ratios are highly variable and probably influenced by the percentage of coal lithologies present in the source rock samples (i.e., coal rich lithologies such as the basal Jurassic and Patchawarra Formations have high pristane to phytane ratios irrespective of the levels of thermal maturity). Pristane to n-C17 ratio is high in the Jurassic source rock extracts when compared to the Permian source rock extracts. Similarly postulated Jurassic sourced group I oils (e.g., Murta oils in Gunna No.1, Jackson No.1 and Hutton and Namur oils in Merrimelia No.8) have a high pristane to n-C17 ratio as compared the group IIa and IIb oils which are probably Permian sourced. However, the levels and the magnitude of differences are higher in the source rock extracts than in the crude oils. Similarly the phytane to n-C18 ratios are slightly higher in the Mesozoic extracts when compared to the Permian extracts. The same ratios for the group I oils are slightly higher than those of the group IIa and group IIb oils. However the differences in these ratios are so small that they are probably not significant.
Fig. 1.24 Comparision of the pristane/n-C17 and phytane/n-C18 ratios of the crude oils and their crude extracts.

- GROUP 1 OILS
- GROUP 2 OILS
- MESOZOIC EXTRACTS
- PERMIAN EXTRACTS
Summary

The correlations between the organic petrological and organic geochemical results used in source rock evaluation on quantitative and semiquantitative bases proved to be good. This shows the complimentary rather than competitive nature of the methods used in source rock evaluation. It is possible to distinguish two main groups of crude oil within the Eromanga Basin reservoirs using some conventional correlating parameters. Comparison of parameters within the source beds indicates some of the possible variations in the properties used in oil-source rock correlations, caused by differences in the composition of the organic matter, different thermal histories, migration of hydrocarbons, and maturation in the reservoir and, hence, the types and levels of uncertainty to be anticipated in oil-source rock correlations.

Correlation between the crude oils and the source rock extracts is poor to fair when n-alkane distribution is used as the correlating parameter. Welte et al. (1975) attributed the high incidence of non-correlation of this parameter as being due to the dependence of n-alkane distribution on temperature histories. Similarly the use of isoprenoid and n-alkane ratios did not show good correlation between crude oils and source rock extracts. Successful oil-source rock correlations cited in the literature come mainly from marine source rocks and cases of good oil-source rock correlations with terrestrial type source rocks are rare. Welte (1965) based upon studies on oil-source rock relationships (Cambrian to Tertiary age) concluded that none of the analysed rock-oil pairs showed complete agreement between all correlation parameters applied.

This study indicates that the relative source potential of the stratigraphic horizons in a sedimentary basin can be reliably assessed using the volumetric abundance of the maceral components, with
vitrinite reflectance as a guide to the levels of thermal maturity. The relative source potentials can be substantiated by using the amount of solvent extractable organic matter (on asphaltene free basis). The individual chemical correlation parameters enable the categorisation of oils of different origin. However correlation between the oils and potential source rock is not very successful owing to the uncertain effects involved in migration.
CHAPTER 8
CONCLUSIONS

1. Within the Cooper/Eromanga Basin sequence hydrocarbon deposits occur in a number of stratigraphic units ranging from Early Permian to Early Cretaceous in age. Organic matter-rich stratigraphic units in both the Mesozoic Eromanga Basin sequence and the underlying Permo-Triassic Cooper Basin sequence, form the potential source rocks for the crude oil reservoired in the Cooper/Eromanga Basin sequence.

2. The relative source potential of selected stratigraphic units from the Cooper/Eromanga Basin sequence was tested using standard organic petrological and organic geochemical techniques, based upon the currently accepted concepts on source rocks and hydrocarbon genesis. Organic petrological studies show that the sections examined are of sufficient maturity for hydrocarbon generation, and most of the lower Jurassic and upper Permian units lie within the peak zone of oil generation.

3. Semiquantitative maceral abundance studies show that, in the Jackson-Naccowlah area, the Permian section has abundant organic matter and has significantly better source potential than the Mesozoic section. Comparing the Jackson and Naccowlah wells (located on the same anticlinal trend) the Permian section in the Jackson No.1 (producing oil well) has more organic matter than that at Naccowlah No.1 (dry well at Naccowlah, but a significant oil discovery made at Naccowlah South subsequent to the completion of the majority of this study). In comparison, the
Mesozoic section in the Merrimelia No.8 (a producing well), has abundant organic matter, but the organic matter content in the Mesozoic section in Packsaddle No.3 (a dry well on the same anticlinal trend as Merrimelia No.8) is low. The Permian section is absent from the crest of both the Merrimelia and Packsaddle structures but is present downflank. In the Merrimelia/Packsaddle area the Permian section, the Gidgealpa group, where present, has good source potential.

4. Crude oil geochemistry suggests that the crude oils examined from the Cooper/Eromanga Basin sequence belong to two distinct groups, named here group I and group II oils. Each group has a distinctive n-alkane distribution profile and alkane parameter characteristics. Group II oils can be further subdivided into two subgroups based upon the variations in the n-alkane distribution profiles.

Group I oils comprise the crude oils in the uppermost reservoir horizon (Murta Member) and the crude oils reservoired at Merrimelia No. 8. They have an n-alkane distribution profile with a low molecular weight hydrocarbon predominance. Normally this is characteristic of mature oils, but alkane parameters of genetic significance such as pristane to n-C17 ratios and phytane to n-C18 ratios suggest that these oils are immature. In contrast the waxy group II oils are reservoired in the lower Jurassic stratigraphic units (Westbourne Formation and Hutton Sandstone) in the Jackson area, have alkane parameters characteristic of relatively mature crude oils. Pristane to phytane ratios are consistently high, although variable, in all
crude oils (groups I and II) examined indicating the predominantly terrestrial nature of the source material. Therefore the existence of two distinct families of crude oils should be due mainly to differences in the maximum levels of thermal maturity attained by the source material possibly with some influence from organic matter type.

5. A good correlation exists between the microscopically determined, volumetric abundance of organic matter and the solvent extractable organic matter content in the source rock samples. Deviations from this relationship occur in several stratigraphic units and these could be due to such factors as the presence of finely dispersed organic matter not observed in the microscopic studies (e.g., Murta Member, Jackson No.1), marginal thermal maturity attained by the organic matter (e.g., Murta Member, Merrimelia No.8) and the high abundance of inertinite in some units (e.g., Toolachee Formation, Naccowlah No.1) and the possibility of oil bathing. Samples rich in coaly matter show a high solvent extractable organic matter content, rich in asphaltenes. Pristane to phytane ratios are high, although variable, in all extracts confirming the predominantly terrestrial origin of the source matter. Both organic petrological and organic geochemical studies of this source rock suggest that in the Jackson/Naccowlah area the Permian section has abundant organic matter and is probably the main source of the hydrocarbons reservoired in the area, with possible lesser contributions from the Mesozoic source rocks. In contrast, the Mesozoic section in the Merrimelia No.8 contains abundant organic
matter, and is probably the main source for the crude oils reservoired in the Merrimelia No.8. For the Merrimelia/Packsaddle well pair, the Packsaddle section is poor in organic matter and perhaps this may be the reason for the lack of commercially viable reservoirs of hydrocarbons in Packsaddle No.3 and possibly, by extension in the Packsaddle structure. However, in the Jackson/Naccowlah well pair, the Permian section in Naccowlah No.1 contains abundant organic matter and the lack of hydrocarbons in Naccowlah No.1 may be a result of non-accumulation (i.e., lack of trapping) or invalid reservoir tests rather than non-generation. Subsequent discovery of high wax group II type oil in the Hutton sandstone in Naccowlah South No.1 substantiate this argument.

6. Oil-source rock correlation between the Mesozoic source rock extracts and the group I type oils, using the n-alkane distribution profiles, is fair to good. Similarly a fair to good correlation was also observed between the n-alkane distribution profiles of group IIb oils (e.g., Hutton oils in Chookoo No.1 and Naccowlah South No.1) and the source rock extracts from the basal Jurassic and the Patchawarra Formations. However only poor correlation was observed between the high wax group IIa type oils and any of the source rock extracts. The n-alkane distribution profiles in the high wax group IIa oils may be a secondary profile generated as a result of migration or of post accumulation maturation within the reservoirs.
7. Alkane parameters (ratios) of genetic significance such as the pristane to \textit{n-C}_{17} ratios and the phytane to \textit{n-C}_{18} ratios are high in group I (probable Mesozoic sourced) oils compared to the group II oils of presumed Permian origin. Similarly these alkane parameters are high in the Mesozoic source rock extracts, compared to the Permian source rock extracts. The absolute values for the source rocks are always considerably higher than corresponding values for the crude oils.

8. The study undertaken indicates the desirability of integrating studies using petrographic techniques for determining maturity and source rock potential with those on extractable organic matter and the value of integrating the results from both of these techniques with crude oil compositional data. It has been possible to indicate reasons why particular structures may not contain commercial hydrocarbon reservoirs (Packsaddle structure) and to indicate structures that have a higher probability of containing commercial hydrocarbon reservoirs than was indicated by the initial wildcat (structure near the Naccowlah No.1 wildcat). Oils in the vicinity of the Jackson field are likely to have been sourced dominantly from the Permian section whereas those in the Merrimelia field could be sourced from the Mesozoic. The Permian section on the flanks of the structure may also be a significant source. The oils reservoired in the Murta Member form a distinctive suite and may represent oils generated from the source rocks within the Murta Member at relatively low levels of maturity.
Appendix 1

Summary of Stratigraphy

Naccowlah No.1 - Location: Lat: 27°29'08.88"S
Long 142°06'40.76"E
Seismic Line - 80-kGL.SP 234

Elevation. G.L. 80.31m KB = 84.26
M.S.L. 0 - Post Adelaide

Undifferentiated (Surface - Toolebuc) - Quartz sandstone, claystone and
minor siltstone, coal and carbonate

Toolebuc 910m - claystone and minor coal.
Early Cretaceous

Roma Formation. 927m - mainly claystone with minor siltstone and
carbonate

Transition Beds. 1247m - mainly calcareous sandstone with minor claystone
and siltstone

Mooga Formation

Murta Member. 1339m - mainly sandstone with minor siltstone and claystone
(Sampling up of the whole section)
Late Jurassic-Early Cretaceous

Namur Sandstone Member. 1423m - mainly coarse grained sandstone with
traces of carbonate and claystone
Late Jurassic

Westbourne Formation. 1500m - Fine grained sandstone, siltstone and
claystone

Adori Sandstone. 1549m - Mainly fine grained sandstone with minor
siltstone and claystone
Mid-Late Jurassic

Birkhead Formation 1618m - Mainly fine grained sandstone with subordinate
claystone and minor siltstone
Early-Late Jurassic

Hutton Sandstone. 1678m - Mainly fine grained sandstone with traces of
claystone
Early Jurassic

Basal Jurassic. 1727m - Mainly claystone and fine sandstone minor
siltstone and coal. Oil cuts in claystone
Late Permian - Early Triassic

Nappamerri Formation. 1793m - Claystone and minor sandstone

Late Permian

Toolachee Formation. 1834m - Claystone and siltstone. Seven coal horizons maximum up to 1m thick

Early Permian

Patchawarra Formation. 1917m - Mainly sandstone coarsening down the sequence. Minor claystone in coal intervals

Pre-Permian. 2081m - Metasiltstone and claystone
Jackson No.1

Elevation: 55.16m G.L. Location: Latitude: 27°36'36"S
M.S.L.O. - Port Adelaide Longitude: 142°25'12"E
59.74 KB Seismic Line - 148, Line 81-KWG

Early-Late Cretaceous to Recent

Undifferentiated Surficial to Winton Formation

Surface - Claystone with minor siltstone and fine sandstone. Traces of carbonate and coal

Mackunda Formation. 366m - Medium grained sandstone and claystone minor carbonate and siltstone

Early Cretaceous

Allaru Mudstone. 472m - Mainly claystone with traces of carbonate and siltstone

Toolebuc Formation. 682m - Claystone, traces of siltstone

Wallumbilla Formation. 690m - Claystone, traces of carbonate and sandstone

Transition Beds. 1022m - Medium to coarse grained sandstone claystone and minor siltstone, trace of carbonate
D.S.T.1 1026-1048 - no show.

Mooga Formation

Murta Member. 1098m - Medium to coarse grained sandstone, siltstone and minor claystone, trace of carbonate
D.S.T.2 1105-1113 - 338 BOPD
D.S.T.3 1131-1141 - 1600 BOPD

Late Jurassic - Early Cretaceous

Namur Sandstone Member. 1172m - Medium to coarse grained sandstone, minor siltstone and trace carbonate

Late Jurassic

Westbourne Formation. 1271m - Medium to fine sandstone, siltstone, traces of carbonate and claystone
(41.4° API at 60°F) D.S.T.4 1313-1330m - 188 BOPD
(41.4° API at 60°F) D.S.T.5 1330-1349m - 1165 BOPD

Adon Sandstone. 1355m - Fine to coarse grained sandstone with interbedded siltstone, trace carbonate

Mid-Late Jurassic

Birkhead Formation. 1383m - Medium to fine grained sandstone and minor siltstone. Four coal intervals.
Early-Mid Jurassic

Hutton Sandstone. 1430m - Medium to coarse grained sandstone, traces of siltstone and claystone. Two thin coal seams near the bottom  
(40.0° API at 60°F) D.S.T. 6 1429-1436 - 1325 BOPD  
(40.0° API at 60°F) D.S.T. 7 1429-1455 - 2375 BOPD  
Oil water contact 1463m

Late Permian

Toolachee Formation. 1497m - Claystone, siltstone and medium to fine grained sandstone. 10 coal intervals up to 3m thick

Early Permian

Roseneath Shale. 1571m - Siltstone with traces of claystone

Patchawarra Formation. 1594m - Fine to medium grained sandstone, minor siltstone and claystone. 7 coal intervals, maximum thickness up to 7 metres

Pre-Permian 1706m - Light grey metasiltstone with minor very light grey metasandstone

T.R. 1746m
Merrimelia No.8

Elevation: G.L. - 41.45m
K.B. = 46.89m
M.S.L. 0 - Port Adelaide

Location:
Latitude: 27°43'68"S
Longitude: 140°11'15.78"E
Seismic Line: SP138, Line 81-KXA

Recent to Early Cretaceous

Superficial and Blanchewater Formation.- Mainly claystone with subordinate siltstone and sandstone. Minor carbonate.

Mooga Formation.

Murta Member. 1556m - Mainly siltstone with traces of carbonate

Early Cretaceous-Late Jurassic

Namur Sandstone Member. 1601m - Mainly fine to coarse grained sandstone. Minor siltstone.

Late Jurassic

Westbourne Formation. 1683m - Fine sandstone and siltstone

Adori Sandstone. 1788m - Fine to medium sandstone

Early-Mid Jurassic

Birkhead Formation. 1812m - Siltstone and fine sandstone. Sandstone content increases towards the bottom.
D.S.T.1.1859-1880m - 190 BOPD

Early Jurassic

Hutton Sandstone. 1874m-D.S.T.2.1847-576 BOPD
Fine to medium grained sandstone with minor siltstone

Basal Jurassic. 2073m - Coarse grained sandstone with subordinate siltstone and minor coal

Pre-Permian. 2191m - Sandstone with thin siltstone interbed
T.D. 2225m
Merrimelia No. 5

Elevation: 35.66 G.L.  
40.84m KB

Location: Latitude: 27°46'30"S  
Longitude: 140°09'20"E

Tertiary - Surface - Sandstone and minor claystone. Sometimes glauconitic

Cretaceous

Winton Formation. 158m - Dominantly siltstone with minor mudstone, sandstone and shale

Tambo Formation. 908m - Sandstone and siltstone with minor mudstone. Trace limestone

Roma Formation. 1216m - Siltstone, shale, very minor sandstone and limestone

Jurassic

Hooray Sandstone. 1539m - Interbedded sandstone siltstone and shale

Westbourne Fm. equivalent 1765m - Sandstone with minor siltstone

Adori Sandstone. 1820m - Poorly sorted sandstone with traces of siltstone

Birkhead Formation. 1853m - Interbedded sandstone, shale, siltstone and coal

Hutton Sandstone. 1954m - Sandstone with interbeds of shale and coal

Triassic

Chandos Formation. 2140m - Sandstone with interbedded siltstone and shale

Permian

Gidgealpa Formation. 2266m - Interbedded sandstone, siltstone and shale. More sandy towards the bottom

Merrimelia Formation. 2384m - Conglomeratic sandstone, with interbedded siltstone and shale

Innaminka Red Beds. 2722m - Red fissile shale.

T.D. 2738m.
Packsaddle No.3

Elevation: 128.28 G.L.  
Location: Latitude: 27°31'30.16"S  
131.21 KB  
Longitude: 140°41'28.03"E

Undifferentiated - Surface - Siltstone and minor sandstone

Lower Cretaceous

Transition Beds. 1376m - Siltstone interbedded with fine grained sandstone

Mooga Formation.

Murta Member. 1474m - Siltstone and fine sandstone

Namur Sandstone Member. 1518m - Mainly fine sandstone and minor siltstone

Upper Jurassic

Westbourne Formation. 1600m - Siltstone interbedded with fine grained sandstone

Adori Sandstone. 1677m - Fine to medium sandstone and minor siltstone

Upper-Middle Jurassic

Birkhead Formation. 1735m - Fine grained sandstone and interbedded siltstone

D.S.T.3 1765-1786 - trace if immulsified oil

D.S.T.4 1794-1804 - no show

Middle-Lower Jurassic

Hutton Sandstone. 1801m - Sandstone with minor siltstone. Few coal seams near the base

Middle-Lower Triassic

Nappamerri Formation. 1986m - Siltstone and fine grained sandstone

Lower Permian

Merrimelia Formation. 2169m - Sandstone and minor siltstone

Unnamed Pre-Permian. 2198m - Crystalline basement rocks

T.D. 2222m.
APPENDIX 2

The Organic Matter Abundance Factor (O.M.A.F.)

The concept of the Organic Matter Abundance Factor (O.M.A.F.) is introduced to assess the relative organic matter abundance in the ditch cuttings on a semiquantitative basis. The nature of these samples usually does not permit a reliable assessment of the organic matter using conventional point counting techniques and hence the O.M.A.F. assessment is preferred.

Cutting samples were made into solid blocks in a cold setting resin and the blocks were then cut in vertical plane and the cut surfaces polished. The organic matter and the relative amounts of the different macerals were assessed for each sample using both reflected light and fluorescence mode microscopy. In the O.M.A.F. system about 50 grains (rock fragments) were counted by several cross traverses perpendicular to the "planes of sedimentation" in the polished sample. For each grain the volumetric abundance of different maceral groups and the total maceral abundance is visually estimated and recorded in a special data sheet. This sheet displays the following features:

1. columns for different rock types including coal lithologies;
2. within each rock type different columns for different maceral groups and total d.o.m.; and
3. a visual aid to assist the assessment of volumetric abundance.

Once recorded this sheet has the advantage of displaying:

1. total abundance of different maceral types at different levels of abundance (0.5%, 0.5-1.0%, 2.0%);
(2) the volumetric distribution of different macerals within individual lithotypes; and

(3) a histogram of different lithological types present in the sample.

The maceral abundance data so obtained is converted into a frequency factor called the Organic Matter Abundance Factor (O.M.A.F.). The O.M.A.F. values can be calculated for various levels of abundance, but for practical purposes levels 1% and 2% abundance are preferred. The O.M.A.F. for a particular level of abundance, i.e., 2% abundance, is calculated in the following way:

\[
\text{O.M.A.F. for individual maceral} = \frac{\text{No. of grains with 2.0\% maceral} \times 100}{\text{No. of grains counted} - \text{coal grain}}
\]

\[
\text{O.M.A.F. for total d.o.m.} = \frac{\text{No. of grains with 2.0\% d.o.m.} \times 100}{\text{No. of grains counted} - \text{coal grain}}
\]

\[
\text{O.M.A.F. for coal} = \frac{\text{No. of grains of coal} \times 100}{\text{No. of grains counted}}
\]

For each sample, the O.M.A.F. values for individual macerals and the total d.o.m. is plotted against the depth. Such a data display will have the following advantages:

(a) gives a semi-quantitative picture of the abundance of organic matter types in different sampled stratigraphic horizons at a glance; and

(b) among the organic rich stratigraphic horizons, it is possible to discriminate between horizons of differing source potential, on the basis of relative amounts of exinite contributions towards d.o.m.
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ADDENDUM


