Eromanga Basin exploration surged in Queensland after the discovery of the Jackson field in 1982, but has ebbed in the last 20 years. Perceived exploration risks are:

1. Oil generation and migration peaked in the mid-Cretaceous before much of the anticlinal structuring, so that modern structure is an uncertain guide to Cretaceous migration paths. Prospects away from producing fairways carry a charge risk.
2. Permian coals are generally credited with sourcing most of the oil and gas in the Cooper-Eromanga Basin (Heath et al, 1989). In Queensland the Permian largely drains to the southern flank and the northern flank is thought to have a high charge risk.

This study covers 100,000 km². It used sonic logs to determine the amount of Tertiary erosion, thus allowing the preparation of structure maps restored to mid-Cretaceous time. Maturity maps of the Birkhead and Poolowanna Formations were computed from a reflectance/restored temperature algorithm based on 50 wells. Source rock thickness maps and an oil expulsion model based on Pepper and Corvi (1995a, 1995b) then allowed oil expulsion to be mapped regionally.

The study produces the key results that could be expected from 3D earth modelling, but with great savings in time and money.

The study demonstrates an oil kitchen at both Poolowanna and Birkhead stratigraphic levels in the vicinity of Tanbar-1. Secondary migration losses are speculative, but modelling shows that hundreds of millions of barrels of oil from each formation have migrated west towards the Curalle ridge, north to Inland and Morney, and southeast to Mt Howitt. The Inland oil field is presently an isolated anomaly on the northwest flank of the basin, but this study suggests that further exploration in the area could be successful.

**KEYWORDS**

Eromanga, Cooper, stripping, restoration, temperature, Jurassic, source, oil, migration.

**INTRODUCTION**

Eromanga Basin exploration surged in Queensland in the 1980s after the discovery of the Jackson field in 1982 but has been at a low ebb for the last 20 years.

There have been many publications reviewing the exploration potential of the Cooper-Eromanga Basin—see for example Kantsler et al (1984) and Gilby and Mortimer (1989). Exploration has been much more successful in the South Australian portion and most geoscience studies have concentrated on that part of the basin.

Perceived exploration risks in the Queensland portion are:
1. oil generation and migration peaked in the mid-Cretaceous, but closures were largely formed in the Tertiary, so modern structure is an uncertain guide to Cretaceous migration paths. Prospects away from producing fairways carry a charge risk.
2. Permian coals are generally credited with sourcing most of the oil and gas in the Cooper-Eromanga Basin (Heath et al, 1989). In Queensland the Permian largely drains to the southern flank and the northern flank is thought to have a high-charge risk.

This study evaluates the potential of Jurassic kitchens in the Queensland part of the Eromanga Basin (Fig. 1) and reconstructs mid-Cretaceous structure as a guide to oil migration. The most obvious approach would be a classic 3D basin modelling project, but this could take far too long and cost a great deal. This project devised a workflow that gave almost equivalent results within a reasonable time frame and budget.

Sonic logs from 107 wells were examined to determine the amount of Tertiary erosion, thus allowing the prepara-
tion of structure maps restored to mid-Cretaceous time. Maturity maps of the Birkhead and Poolowanna Formations were computed from a reflectance/restored temperature algorithm based on 50 wells. Source rock thickness maps and an oil expulsion model based on Pepper and Corvi (1995a, 1995b) then allowed oil expulsion to be mapped regionally.

Figure 1. Location map.

Figure 2. Stratigraphic column.
Regional structure map. Top Cadna-owie Formation (C Horizon) from National Geoscience Mapping Accord, Cooper-Eromanga Basins Project. Depths in m below sea level.

Figure 3 (above). Regional seismic section (see Figure 4 for line location).

Figure 4 (below). Regional structure map. Top Cadna-owie Formation (C Horizon) from National Geoscience Mapping Accord, Cooper-Eromanga Basins Project. Depths in m below sea level.
ESTIMATING EROSION

Numerous workers have remarked that after mid-Cretaceous deposition ceased, there was widespread uplift, erosion and periods of compressional structuring. It has been widely suggested that generation and migration peaked in the mid-Cretaceous at maximum burial and that closures formed in the Tertiary may have missed out on charge. Exploration has been aimed at locating present day structures that were first closed in the mid-Cretaceous. Traditional methods of flattening on a shallow seismic marker are not very successful because

1. there are no shallow markers in the poorly reflective alluvial deposits of the Winton Formation; and,
2. hundreds of metres of section have been stripped from the area and seismic interpretation cannot define any structural growth that may have occurred immediately prior to cessation of deposition.

Two workers have attempted to determine mid-Cretaceous structure by estimating the amount of stripping using compaction trends determined from sonic velocity. Both focussed on the South Australian part of the basin and neither covered the whole of the area of interest for this study.

Rodgers et al (1991) used gross interval velocities (presumably from well velocity surveys) for the mudstones of Allaru and Wallumbilla Formations. The method was demonstrably successful because they showed that computed maximum burial depth was a much better predictor of porosity in the Hutton Sandstone than its present burial depth. Their structural results, however, were published as a very small map, limiting their use.

Mavromatidis and Hillis (2005) used sonic logs in 205 wells to compute relative uplift for each of seven stratigraphic intervals spanning the Winton to Hutton formations. They published their detailed methodology and provided an internet link to the raw data. Sonic logs are plotted as transit time (rather than velocity) because compaction effects tend to give a straight line when plotted against depth and this simplifies stripping calculations. Several problems occur in using this method. Many wells do not have sonic logs over the shallow section where sensitivity to compaction is greatest. The data quality of many sonic logs tends to be poor in the shallow section, and recognising a siltstone compaction trend requires editing of noise. This noise consists of electronic noise where readings are far too slow to be credible (transit time sometimes greater than sea water; 189 microseconds/ft) and lithologic noise where fast (possibly calcite cemented beds) biases average siltstone velocity to higher values. Mavromatidis and Hillis (2005) do not discuss editing and their data are not used here.

The present study only examines the shallowest unit, the Winton Formation, because it is most sensitive to compaction effects and is mostly a siltstone over the study area. This study involved plotting the sonic log along with a gamma ray log to identify sandy beds and noise. A siltstone compaction trend was estimated manually on cross-plots. This is preferable to using a linear regression that may be precise mathematically but would mostly incorporate too much noise (Fig. 5).

Mavromatidis and Hillis (2005) found that the Winton Formation with the slowest velocity profile (i.e. least compacted) occurred in Beanbush–1 in South Australia. The well is believed to be at maximum burial or close to it, because the Winton Formation is covered by 238 metres of Tertiary section, which will compensate for any post-Winton erosion. The interpreted compaction trend (Transit time = 194 - 0.072 * depth; Fig. 6) is used as a reference for zero stripping (Fig. 7).
Some 107 wells were examined to estimate the amount of stripping and the results were used in two ways: to restore structural maps to time of maximum burial and to restore cross sections.

**Figure 6 (left above).** Gamma ray and sonic logs for Winton Formation in Beanbush–1. The interpreted trend line is used as a reference for zero stripping.

**Figure 7 (left).** Example of stripping from Copai–1. The interpreted Copai–1 trend is offset from the Beanbush trend by 22 microsec/ft, or 306 metres using the Beanbush gradient.
Restored structure maps

Previous workers have published stripping maps based on gridding and contouring the stripping values determined at wells. This provides a general guide to identify early traps but is not sufficiently detailed. The present day Eromanga structure map (Fig. 4) is dominated by structural highs caused by inversion anticlines on high angle faults (Fig. 3). Since many of the wells are located on such highs, contouring the stripping values will not capture the variations in stripping due to structural complexity between the wells. In this study we assume that at the end of Winton deposition the Eromanga Basin was a gentle sag. This is supported by isopach maps of Eromanga stratigraphic units based on well intersections (Draper, 2002) which show that the basin was a gentle sag and seismic sections that show no evidence of earlier Cretaceous structural growth.

This study uses the regional depth grids for the ‘C’ (top Cadna-owie) and ‘P’ (top Permian) seismic horizons sourced from the National Geoscience Mapping Accord Cooper-Eromanga Basins Project. The estimate of stripping at each well was added to the modern Cadna-owie burial depth, followed by gridding and contouring. Although this map is based on widely scattered wells, the gentle structuring of Eromanga beds at the end of Winton deposition suggests that it is a reasonably accurate isopach for the interval top Winton to Cadna-owie. The Winton Formation is relatively uniform and fine grained across the study area, suggesting that there was little topographic relief. Thus at end-Winton deposition, although the elevation above sea level is unknown, the surface was flat enough to use as a datum. That is, the isopach map can be used as a restored ‘C’ structure map (Fig. 8). In this process, errors due to ignoring the distinction between ground level and Kelly bushing, and the possibility of differential compaction are believed to be small and not material.

The general structure is believed to be reliable, particularly where contouring of features is controlled by several wells (e.g. highs at Morney and Wareena). Features based on a single well are suspect because of the possibility of poor log quality, unrecognised lithological variation, or mistaken interpretation of the siltstone compaction trend.

A stripping map (Fig. 9) was generated by first preparing a present day Cadna-owie burial depth grid (‘C’ structure map plus elevation grid) and subtracting it from the Restored Cadna-owie structure grid.

This stripping map shows the Curalle-1 and Morney North-1 wells are located on anticlines that are particularly deeply stripped.

A Restored Hutton structure map (Fig. 10) was computed by generating a top Cadna-owie to top Hutton isopach map from well intersections and adding its grid to the Restored Cadna-owie structure grid. The isopach is typically smooth and the resulting Hutton map is believed to be reliable in general if not in detail.

Most Eromanga oil reserves in Queensland are found in the Hutton Sandstone and much of the oil has migrated laterally at this level. The structure map restored to end-Winton deposition is believed to be the best avail-

![Figure 8. Restored Cadna-owie structure map. Computed Top Cadna-owie structure (m) at end-Winton deposition.](image1)

![Figure 9. Thickness of stripped Winton Formation. Posted values (metres) were determined from sonic logs.](image2)
able guide to the main phase of secondary oil migration (i.e. migration in a carrier bed after the hydrocarbons have left the source rock through primary migration). A restored P horizon map (Fig. 11) was generated by adding the stripping grid, the topographic grid and the modern P depth structure grid. The Permian beds (belonging to the Cooper Basin) have a much more restricted distribution than the Jurassic-Cretaceous Eromanga Basin. The Permian sequence has numerous intra-formational shales and secondary migration will largely follow the Permian bedding until it reaches a truncation edge where it will migrate into the Eromanga reservoirs (Heath et al, 1989). The restored Permian structure is asymmetric with virtually all the drainage towards the southeast flank.

**Figure 10.** Restored Hutton structure. Posted values are sum of interpreted stripping thickness and modern Hutton burial thickness. Top Hutton (m) restored to end-Winton surface.

**Figure 11.** Restored ‘P’ Horizon. Top Permian structure (m) restored to end-Winton surface.
RESTORED SECTIONS

Some restored log correlation sections were prepared and oil saturation was plotted on them to determine whether early oil charge marked by residual saturation corresponded better to restored or present day structure.

A log correlation section (Fig. 12) between wells Copai–1–Morney–1–Inland–1–Cuddapan–1–Tanbar North–1 is datumed on sea level.

Details of the Hutton Sandstone are shown in Figure 13. Information on oil occurrence has been added from the mudlog. A live oil column (recognised by 100% bright fluorescence and/or oil recovered on test) is marked in brown; a residual oil column (10–80% fluorescence; mostly water on test) is shown in green. Indeterminate tight columns (no formation fluid recovered on test) that could be live or residual are also shown in green. Figure 13 shows that the Morney High has a 20 m residual oil column at the crest of the anticline. There appears to be a common paleo-oil-water contact at -1,274 mSS, and any variation in elevation can be attributed to lithology effects on the transition zone and mud logging accuracy—there is no
evidence for structural growth since charging. The present anticline has a closure of 130 m and an area of 268 km$^2$ (Fig. 14) so the closure was far from full to spill. The Inland Field has a 20 m live oil column overlying a 20 m residual column. Again the structure is far from full-to-spill and there is no sign of post-charge restructuring.

The stripping data were used to restore the Copai–1–Tanbar North–1 section to structure at end-Winton deposition (Fig. 15)

In restoring the Copai–Tanbar North section to post-Winton structure, the three Morney wells and three Inland wells were composited. The accuracy of the stripping estimates is about 30 m at best, so the closely spaced crestal wells cannot provide details of restored structure of the fields. The sonic logs were overlaid to determine a single best fit for a restored Winton thickness for the two fields (947 m for Morney; 1,070 m for Inland). Although this variation might suggest relative structural growth during Winton deposition, the thickening is simply consistent with the general basinward thickening of the Eromanga units.

The restored section (Fig. 15) and restored structure map (Fig. 10) show that at end-Winton at Hutton level, Morney was a distinct structural nose, and that Copai was at about the same level. There are insufficient wells in the area to determine whether there was a closed structure in the vicinity of Morney, or to the northwest as indicated by the contouring.

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**Figure 14.** Structure map for Hutton Sandstone on Morney High. Depths metres below sea level.

**Figure 15.** Log correlation section restored to structure at end-Winton deposition.
Temperature

Present day temperature gradients were determined in some 150 wells in the study area. Well completion reports were examined for temperature data from drill stem tests and wireline logs. Logging temperatures were corrected by the Horner plot method where the necessary time information was available. For a few wells there was insufficient information to make the extrapolation to infinite time, and an arbitrary 15% was added to the first log temperature (in Celsius). A linear gradient was fitted to the data, anchoring it at the surface at 21°C and bearing in mind that the measured and extrapolated temperatures are more likely to underestimate than overestimate the formation temperature. Use of a linear gradient is a crude approximation to reality but is believed to be fit-for-purpose. In this case the purpose was to estimate the temperature of source rocks in potential Jurassic kitchens at maximum burial, and since these are at depths similar to the total depth of many wells, errors are not likely to be large.

Temperature gradients were gridded and mapped (Fig. 16)

In this study we assume that there has been no substantial variation in heat flow since the Winton deposition and that maturation of the Jurassic source rocks are best modelled with the present temperature gradients. Some early workers (e.g. Pitt, 1986) found that maturity modelling of wells using present day temperature gradients failed to get a good match with the observed vitrinite reflectance and proposed that there had been a recent increase in temperature gradient. This was based on maturity modelled by the early Lopatin method (Morrow and Issler, 1993). The need to postulate a late heating event is not required if thermal history is estimated using the laboratory-based vitrinite kinetics introduced in the late 1980s. Deighton et al (2003) favoured higher heat flows in the Cretaceous and lower heat flows at around 5Ma based on apatite fission track studies. We are unable to find a suitable physical explanation for these fluctuations in the tectono-stratigraphic record. Our 1D maturity modelling of the wells in the study area is in most cases satisfactory when a constant heat flow is assumed.

Maturity

Sixty wells in the study area have publicly available vitrinite reflectance data compiled by Geological Survey Queensland from open file reports.

Using vitrinite reflectance data to estimate a maturity trend involves a fair degree of interpretation. One problem is operator judgement. Figure 17 shows Rv maximum values from the same well by two separate laboratories. The trend chosen here is a compromise as we are unclear as to the details associated with the datasets. Experience in basin modelling shows that plotting Ro% on a log scale against depth usually makes the trend close to linear, and in basins with limited erosion, a modelled Ro-depth trend commonly emerges at the surface at a value of around 0.25–0.3%.
A second problem for this study is the lower than expected reflectance when vitrinite macerals with a moderate to high hydrogen content occur in a formation. Jurassic coals in the Eromanga Basin have a moderately high hydrogen content (see next section) and suppression can be expected to be endemic. There is no published information on corrected values for the Eromanga Basin. Nevertheless, there is a thesis (Michaelsen, 2002) which compared results for 12 samples of Jurassic rocks subjected to both conventional reflectance measurements and FAMM measurements which use fluorescence intensity to correct for suppression (Wilkins et al, 1992). The results are plotted in Figure 18.

Each bar represents a sample, with the right hand end marking the corrected FAMM value (as Ro mean maximum) and the left hand end the value determined by conventional reflectance measurement. For example a sample of Birkhead Formation in Poonarunna–1 at 1,622.78 m is immature (0.4% Ro max) by conventional methods but mature (1.04%) by the FAMM technique. The values are arranged vertically on a log scale using the FAMM value. Thus the plot simulates the pattern expected in a well where the FAMM value is regarded as correct and log Ro increases linearly with depth. The distance of the left hand end away from the trend line indicates the amount of suppression.

This means that all the Jurassic samples are suspect, and if fitting a trend to Jurassic samples in a well, the trend line should be placed on the high side of most or all conventional readings. Several wells have data from the Triassic and Permian and these values are much more reliable. Either the beds are sufficiently mature (over about 1.5% Ro) that suppression is not a problem, or the kerogens were sufficiently low HI (below about 150) that suppression is not a problem. In this study, where available, the Ro-depth trend lines were fitted to the Triassic and Permian samples and Jurassic samples were largely ignored (Fig. 19).

After estimating approximate gradients for organic matter maturity versus depth in the wells, the next step is to generate maturity maps. Simply gridding the well data provides a general overview but does not have the detail due to structural complexity between wells. To get this detail the first step is to multiply the stripping grid (Fig. 9) by the temperature gradient grid (Fig. 16) to determine how much hotter the beds were at maximum burial than at present. This value can be added to the present day temperature for each formation to get a maximum temperature.

Figure 20 plots log of vitrinite reflectance against maximum temperature for the top of the Poolowanna Formation. Since a plot of Log Ro against depth is roughly linear, and since a plot of temperature against depth is roughly linear, a cross plot of Log Ro against maximum temperature should also be roughly linear.

The amount of scatter is not altogether surprising given the amount of uncertainty in the contributing measurements (reflectance, temperature and uplift). A useful equation for the relationship was generated by linear re-
gression after deleting some outlying values. Lynwood–1 was omitted because the temperature data are bad—the log headers have conflicting information. Thunda–1 was omitted because the temperature values are too low to

**Figure 20.** Plot of Log Reflectance against maximum temperature for Poolowanna Formation.

**Figure 21.** Birkhead maturity. Start of oil expulsion window (0.8% Ro) highlighted.

**Figure 22.** Poolowanna maturity. Oil expulsion window (0.9–1.3% Ro) highlighted.

**Figure 23.** Permian maturity (top Toolachee Formation). Oil expulsion window (0.95–1.3% Ro) highlighted.
areas is marginal maturity, and modelling the top of the formation gives a conservative result.

SOURCE QUALITY

Open file information on Cooper-Eromanga source rocks involves a variety of analytical techniques. In this study we have focused on Rock-Eval analyses because the Hydrogen Index (‘HI’) is critical to developing a generation and expulsion model. Three units were considered as potential source rocks—Birkhead, Poolowanna and Permian. Although the Jurassic kitchens are of limited extent, HI analyses were considered from all wells in the study area on the grounds that the stratigraphy appears uniform and all the sparse data are needed.

Birkhead Formation

The Birkhead Formation has been documented as a good potential source rock in South Australia (Michaelsen and McKirdy, 2006; Boult et al. 1998). A plot of HI/TOC for 90 Birkhead samples from 20 wells in the study area in Queensland is given in Figure 24.

Most of the samples were sandy cuttings with low Total Organic Carbon (‘TOC’) and with HI marginal for oil generation. There is, however, a coaly component with useful source potential. Ten coaly samples within the range 5%–<10% TOC had an average HI of 236 and nine samples with TOC ≥10% had an average HI of 403. In a later section, the HI of the kerogen is used in an expulsion model in which there is a large adsorption threshold, so a simple bulk average HI would be misleading. Instead the values are grouped into two or three bands. Thus expulsion calculations were done on a notional composite Birkhead coal composed of 53% HI 236 and 47% HI 403.

The usual approach to modelling generation is to assume that an immature sample has a maximum HI and that it decreases with generation and expulsion. A characteristic of coaly source rocks however, is that when they mature, molecules are restructured to give a higher Effective HI immediately prior to expulsion (Sykes and Snowdon, 2002). This has been well documented for Taranaki Basin coals (Sykes and Snowdon, 2002, Fig 25). Although this plot is for New Zealand coals from the Late Cretaceous and Early Tertiary, the shape of the band is believed to be a reasonable generic guide to the change in HI with maturity.

Bargo–1 was omitted because it only has four vitrinite samples that are too immature to give a reliable gradient. Opal–1 was omitted because there are only two immature samples. Gumla–1 and Talgeberry–2 are dropped because the wells are too shallow to get a reliable maturity gradient. Bunya–1 was dropped because the restored temperature was much too low for the observed Ro% although the reason could not be identified.

A maximum temperature map can be generated for each formation from the temperature gradient map and restored structure map. This can be used with the regression line of Figure 20 to compute a maturity map. See Figures 21, 22 and 23 for Birkhead, Poolowanna and Permian horizons respectively. In each case the top of the unit was modelled because, in the case of the Jurassic, the issue in many
Poolowanna Formation

Samples from the Poolowanna Formation are mostly sandy cuttings and have low TOC and low HI values (Fig. 27). It appears that thin associated shales also have low TOC and low HI. There are no core samples from coals and only a few core samples of coaly shale are included in the data set. For these analyses, only coals and coaly shales can be expected to have HI values adequate for oil expulsion, and subsequent calculations are based on samples with TOC greater than 2.2%.

Only 19 HI analyses are available with TOC >2.2% and they seem to fall naturally into three groups (Fig. 28). Group 1 (5 samples; 26%) has values of around 150 and the kerogen is not expected to expel more than trace quantities of oil (see section on expulsion model). Group 2 (eight samples; 42%) lies along the lower bound and will have had an Effective HI of 230 prior to expulsion. Group 3 (six samples; 32%) lie along the upper bound and will have had an Effective HI of 340 prior to expulsion. This excludes two samples with unrealistic HI values (0 and 652). For the purposes of the expulsion model in this study, the Poolowanna coal is regarded as a composite with three components: 26% ineffective, 42% HI 230 and 32% HI 340. This composite model is not particularly robust but is the best with the available data.

Figure 26. Birkhead samples (TOC>5%) plotted with New Zealand Coal Band.

Figure 27. Hydrogen Index for Poolowanna samples from wells in study area.
Permian coals

In South Australia, Boreham and Hill (1998) indicated that the Patchawarra Formation was the principal source unit, but in this study area the Toolachee Formation has more widespread and thicker coals (Draper, 2002). Boreham and Hill (1998, Table 8.2) cited average HI values of 177 and 214 for the two formations, but in Queensland there is insufficient information to treat them separately. In the study area, there are three wells with Rock-Eval data that intersected both Patchawarra and Toolachee formations (Keilor–1, Mt Howitt–2, and Toby–1). A cross plot of HI against TOC (Fig. 29) indicates that there is no significant difference and that the two units can be combined for Rock-Eval source studies.

**Figure 28** Poolowanna samples (TOC>2.2%) plotted with New Zealand Coal Band.

**Figure 29.** HI / TOC of Permian samples in 3 wells that intersected both Toolachee and Patchawarra Formations.
A plot of HI against TOC for all 19 wells (Fig. 30) suggests that samples with TOC of less than 10% have low HI values, and for this source rock study it is better to focus only on the coaly material.

If plotted against maturity the values fall mostly below the New Zealand coal band. The expulsion model (see later) indicates that an Effective HI of less than 140 will not expel oil, and 10 out of 77 HI values are in this category (average HI about 100). The remaining 67 values appear to have an average Effective HI of around 200 (Fig. 31).

**SOURCE QUANTITY**

**Birkhead Formation**

Sonic logs for 24 wells were assessed for net coal thickness. A criterion was selected for each well based on:

- the coal being distinctively slower than shales;
- the presence of coal on the mudlog and,
- and presence of associated wet gas peaks.

The wells were mostly selected in areas of at least moderate maturity. The values were gridded and contoured to produce Figure 32.

![Permian Analyses](image1)

**Figure 30.** HI/TOC for most Permian samples in study area.

![Permian >10%TOC](image2)

**Figure 31.** Permian samples plotted in relation to New Zealand coal band. An additional (dotted) line is added to show the maturation trend below which no expulsion can be expected.

![Birkhead Formation cumulative coal isopach for wells studied. Larger numerals are contour labels; smaller numerals are](image3)

**Figure 32.** Birkhead Formation cumulative coal isopach for wells studied. Larger numerals are contour labels; smaller numerals are...
Poolowanna Formation

The cumulative thickness of coal and coaly beds in the Poolowanna was estimated visually for 133 wells using open file images of mud logs and composite logs, and wireline logs were used to estimate coal thickness for 25 wells with thick intersections.

A cross plot of the visual estimate and the more accurate log evaluation estimate showed that the visual estimates needed to be scaled by a factor of 74%. The combined results are shown in Figure 33.

Permian

Draper (2002) published coal isopach maps for the Toolachee and Patchawarra Formations in Queensland (his Figs. 18 and 31). The maps were hand digitised and summed to produce Figure 34 for use in this study.
EXPULSION MODEL

Pepper and Corvi (1995a, 1995b) published a kerogen expulsion model that can be adapted for use with the rather limited Eromanga data.

The model assumes that the kerogen consists of a mixture of labile (oil generative and gas generative) and inert kerogen and that the proportion of labile to inert is given by the Hydrogen Index. Early generated hydrocarbons will be adsorbed onto the kerogen and only expelled after the amount of generation exceeds a threshold. This threshold is estimated at 10% (kg/kg carbon in kerogen) for oil and 2% for gas. The expelled oil must wet out the source rock pores before it can be expelled into a carrier bed for secondary migration. Pepper and Corvi (1995b) considered the amount needed for wetting to be small and in this study it is included in secondary migration losses.

Different kerogens crack at different rates for a given heating history. Pepper and Corvi (1995a) defined a series of organic facies with distinct cracking parameters (Activation Energy (E) and Frequency Factor (A)). The Eromanga coals belong to their ‘Facies DE’ (Terrigenous, non-marine, waxy). The maturity modelling program BasinMod has Facies DE kinetics built in. It was used to generate a plot of Transformation Ratio as a function of Maturity (measured as equivalent Ro%) for a generic burial history (Fig. 35).

A spreadsheet model was built to compute volumes of oil expelled per cubic metre of coal from the following inputs:

- average density of coal (2.0);
- Average coal content of coaly intervals identified on logs (60%);
- Fraction Organic Carbon in coal (70%);
- Fraction organic carbon in oil (85%);
- Potential oil/gas fraction derived from Pepper and Corvi (1995a, Figure 2). In Figure 36 the gas fraction is represented by the equation \( G = -0.089 \ln(HI) + 0.7428 \);
- Hydrogen Index (treated as variable);
- The adsorption thresholds for oil and gas are 10% and 2% respectively (kg hydrocarbon/kg organic carbon; Pepper and Corvi, 1995b);
- From Figure 35, The Transformation Ratio (‘TR’) of Type DE kerogen to oil is given approximately by \( TR = 29.439Ro^5 - 137.2Ro^4 + 244.69Ro^3 - 207.53Ro^2 + 84.579Ro - 13.314 \) where Ro is % vitrinite reflectance;
- The transformation ratio of Type DE kerogen to primary gas is given approximately by \( TR = -0.3944Ro^5 + 3.4223Ro^4 - 11.331Ro^3 + 17.399Ro^2 - 11.424Ro + 2.6629 \) where Ro is % vitrinite reflectance;
- The TR function is a graphical approximation that can give a value above 1.0 at high maturities, and the value is truncated at the maximum value of 1.0; and,
- Eromanga oil typically has a density of 0.80 g/cc (45° API).

Relatively little gas is found in Eromanga reservoirs, presumably because it has been removed by water washing (Boreham and Summons, 1999). Thus gas production (Primary and Secondary Cracking) is ignored in this study.

Figure 35. Plot of Transformation Ratio as a function of Vitrinite Reflectance.

Figure 36. Gas fraction as a function of Hydrogen Index redrawn from Figure 2 of Pepper and Corvi (1995a).
Expulsion curves were computed for kerogens with Hydrogen Indices of 230 and 340 and are plotted in Figure 37. The kerogen with the lower HI has to reach higher maturity before expulsion starts because of the adsorption threshold.

As noted earlier, the Birkhead kerogen is regarded as a composite of kerogens with HI of 236 (53%) and 403 (47%). The expulsion curve is plotted in Figure 38 and an approximate equation fitted. The comparable expulsion curves for composite Poolowanna and composite Permian coals were added and curves were fitted to the data (Fig. 38), yielding the following functions:

**Birkhead**

\[
Y = -8.0191X^5 + 58.044X^4 - 163.07X^3 + 220.2X^2 - 140.59X + 33.874
\]

**Poolowanna**

\[
Y = -4.7888X^5 + 34.984X^4 - 99.382X^3 + 136.08X^2 - 88.526X + 21.824
\]

**Permian**

\[
Y = -3.7175X^5 + 27.272X^4 - 77.754X^3 + 106.72X^2 - 69.421X + 16.954
\]

where

- \(Y\) = oil expelled in barrels per cubic meter of coal
- \(X\) = maturity in Ro%

![Figure 37. Transformation Ratio plotted against maturity for HI 230 and 340.](image)

![Figure 38. Plot of oil expulsion against maturity for composite coals in study area.](image)
VOLUME OF OIL EXPELLED

For the Birkhead, the equation for oil expulsion curves can be used, along with the maturity grid (Fig. 21) to compute a grid for expelled oil (BBL/m³ of coal; Fig 39).

The map is largely a reflection of Birkhead maturity except that it is truncated below the expulsion threshold of about 0.8%. This expulsion grid is multiplied by the coal isopach grid (Fig. 32) to get intensity of oil expulsion in million barrels/km² (Fig. 40).

Comparable calculations are done for the Poolowanna and Permian source rocks (Figs. 41 and 42).

The western kitchen around Tanbar is caused by a combination of higher thermal gradient and deeper burial (giving higher maturity) and moderate coal thickness. An apparent kitchen in the northeast is based on a particularly thick coal intersection in Brightspot–1. The sparse well control in the area results in the gridding program extending the kitchen to cover an implausibly large area. The Tanbar kitchen expels more oil from the Birkhead Formation than from the Poolowanna in spite of its lower maturity because the Birkhead coal is thicker and has higher HI.

Figure 39. Oil expulsion (BBL/m³ of coal) from Birkhead coal.

Figure 40. Oil expulsion intensity (MMBBL/km²) from Birkhead Formation.

Figure 41. Oil expulsion intensity (MMBBL/km²) from Poolowanna Formation.
The distribution of oil expulsion from the Permian differs markedly from the Jurassic sources because the Permian expulsion intensity is dominated by coal thickness rather than maturity.

**Volume of oil trapped**

The important question for the oil and gas explorer is not how much oil has been expelled but how much oil might be trapped in commercial accumulations. This is very difficult to estimate in a lightly explored area such as the Eromanga, but studies in well documented basins can give some guidance. There are several possible approaches:

1. **3D basin modelling.** There are so many poorly constrained variables in a large lightly explored area that 3D modelling will have very little predictive ability.

2. **Break down the losses into the various components and try to estimate them using basin analogs.** Losses include:
   - kerogen adsorption losses discussed above.
   - residual source rock saturation.
   - residual carrier bed saturation.
   - losses up faults to surface.
   - losses to outcrop.
   - trapping in subcommercial structural and stratigraphic traps.

   This approach was tried but is not presented here because so many variables were so poorly constrained.

3. **Use an overall basin analog for Petroleum System Efficiency.** This is the percentage of the petroleum actually generated that occurs in identifiable traps (England, 1994). This is similar to the Generation-Accumulation Efficiency of Magoon and Valin (1994) defined as the ratio of the mass of in-place petroleum in traps to the mass of generated petroleum. They provided information on 16 globally distributed petroleum systems. The data are plotted in Figure 43 along with two examples from the North Sea (Goff, 1983) plotted in red.
An arithmetic average for the calculated efficiencies is 10.2%, but this is inflated by a doubtful value of 54% (Goff, 1984). Visual inspection suggests 8% could be used as a general value. The corresponding 92% losses include many different sorts, including kerogen adsorption. Magoon and Valin (1994) list Hydrogen Indices for the petroleum systems in their Table 20.6, and the average is 470. The Pepper and Corvi (1995b) expulsion model as implemented here suggests that for an HI of 470, about 30% is adsorbed and 70% expelled. Thus the efficiency for trapping the expelled hydrocarbon is about 11%. This factor of 11% has been applied to the computed volumes of expelled oil in the study area. In the case of the Birkhead formation, it is assumed that the restored ‘C’ horizon is the best indicator of migration directions and the Petrosys orthocontour facility was used to track the up-dip migration directions (Fig. 44). The area was divided into drainage cells and the volumes computed for each.

Figure 44. Drainage cells for Birkhead kitchen. Drainage is plotted on restored ‘C’ structure (black contours). Colour indicates intensity of oil expulsion from Birkhead source. Potential reservoir volumes were computed from 11 percent of expelled volumes.
The map indicates the potential for trapping the following approximate volumes of oil:

- 420 MMBBL from an area drains northwest before swinging northeast to a closure immediately northwest of Morney. If this putative closure spilled the oil would have headed northwest past Copai–1.
- 150 MMBBL from an area draining north past Inland before joining the Morney closure.
- 130 MMBBL towards Alkina–1.
- 240 MMBBL to a high at Mt Howitt–1.
- 70 MMBBL each towards Wareena–1.

Similar computations are shown in Figure 45 for the Poolowanna kitchen.

Highs at Morney and Mount Howitt attract much of the oil. The possible kitchen farther east centred on Brightspot–1 is too speculative to analyse.

The Permian kitchen has a very different drainage pattern (Fig. 46). The axis of the Cooper Basin is offset to the

Figure 45. Drainage cells for Poolowanna kitchen at Tanbar–1. Drainage is plotted on restored Hutton structure (black contours). Colour indicates intensity of oil expulsion from Poolowanna source. Potential reservoir volumes are computed from 11 percent of expelled volumes.
southeast from the general synclinal axis of the Eromanga Basin. A similar relationship applies to the Permian structure restored to end-Winton time. As a result, the bulk of the kitchen drains southeast with only two small areas draining northwest.

At Permian level only 3% of the expelled oil would migrate north. Along the southeast flank the Permian oil migrates to the edge of the Triassic shales and then climbs stratigraphically as it migrates through the Eromanga Basin reservoirs (Heath et al, 1989). Migration out of the Permian is likely to have started prior to the Winton deposition, so reconstructing migration paths of Permian oil is difficult.

**DISCUSSION AND CONCLUSIONS**

This study is the first publication of Cretaceous migration maps for the Eromanga Basin. The maps cannot be relied on to track precisely where the oil went, but they can be used for estimating the charge risk of exploration prospects. In particular the study demonstrates that there is a good chance of charging prospects with Jurassic oil on the north flank of the basin.

The aim of the study was to produce results similar to a 3D basin modelling study. The workflow was devised based on available data and on previous experience in basin modelling. We are not aware of a similar workflow being published elsewhere though it is unlikely to be unique. Apart from the obvious benefits of vastly lower costs (less hours, less software, less hardware) there is also the benefit of timing. Building a basin model involves importing regional depth maps at numerous horizons so that the modelling has to be preceded by a massive regional mapping project. In this case we were lucky to have the NGMA grids for the ‘C’ and ‘P’ horizons and a uniform Eromanga stratigraphy. This allowed the use of isopachs gridted from sparse wells to interpolate intermediate horizons.

This study has been on a regional scale, covering 100,000 km². Before using the maps on a prospect scale, details of the structural restoration estimates need reviewing. The restoration process involves the present depth to the Winton-Mackunda boundary, but this boundary is transitional and the pick subjective. In this study we used the Well Completion Report picks with some re-adjustments where needed. A consistent re-picking of the boundary through the area would help, while incorporating compaction trends in the Allaru Mudstone may be even more helpful. It may also help to check the sonic log calibration with check shot or VSP surveys where available. The number of wells available for estimating stripping is limited by the tendency in the southwest for wells to lack shallow sonic logs, and the tendency in the northeast for logs in the shallow section to be particularly noisy. It is hoped that in the future operators will record good quality sonic logs across the shallow section and so improve the detail of the restored structure maps.

Figures 21 and 22 show numerous discrepancies between maturity contours and maturity values posted at wells. This is because the contours were derived from the algorithm of Figure 20 and given the scatter in that figure, discrepancies are inevitable. The scatter has several possible causes. It could be due to errors in stripping, temperature and reflectance measurements, and it could be due to the assumptions of an overly simplistic geological model. It seems that much of the variation is due to reflectance measurements on different types of vitrinite, and using a regression line will generate a more predictive maturity map than building a model tied to individual well maturities. In future, Jurassic samples should be examined with a technique that corrects for suppression (for example FAMM or VIRF).

The quality and distribution of available Rock-Eval data are variable, and future wells should acquire sidewall cores from the Jurassic coals for analysis. This study has tried to be conservative, and while analyses of more and better samples would improve confidence in the expulsion results, new analyses are unlikely to make big changes to the outcome of the modelling.

The most speculative of the calculations presented here is the potential reservoir oil volume. There is little opportunity to validate or improve on the analog estimate of 11% migration and trapping efficiency. Even if losses are particularly severe in the Eromanga Basin and the volumes should be reduced by a factor of 10, there is still enough oil to expect charge for commercial accumulations on the northwest flank of the Eromanga Basin.

![Figure 46. Permian kitchen. Two small cells drain northwest. Drainage is plotted on Permian structure restored to end-Winton time (black contours). Colour indicates intensity of oil expulsion from Permian coals.](image-url)
There has been a long-running debate on the relative contributions of Permian and Jurassic source rocks to Eromanga oil accumulations. For the Inland field oil, Boreham and Summons (1999) favoured a Permian origin on the grounds that a plot of Compound Specific Isotope Analysis (CSIA) of n-alkanes showed a negative slope. On the other hand Michaelson (2002) found a sufficient abundance of conifer biomarkers to indicate a mixed origin. The Morney oil was regarded by Boreham and Summons (1999) as having a 'more dominant Eromanga Basin source contribution on the grounds of a flatter CSIA profile and more abundant conifer biomarkers'. From a pragmatic point of view, the Inland and Morney oils are on the same structural high and very likely have the same origin. Furthermore the expulsion and drainage plots in the previous section suggest that a Jurassic charge is very likely and a Permian charge is unlikely, so we favour a Jurassic source in this study.

In discussions on the geochemistry of the oils, the abundance of conifer biomarkers is thought to reflect the evolution and increasing abundance of conifers through the Jurassic and Cretaceous. The general interpretation has been that low levels indicate a Permian source, high levels a Jurassic source, and intermediate levels a mixed source (mixed in the reservoir or during migration). This study has demonstrated the effectiveness of both Poolowanna and Birkhead kitchens in the study area, raising the possibility that the Birkhead provides high conifer biomarker levels but the older Poolowanna coals may contain a lower proportion of conifers and their oils may be mistaken for mixed oils. Oil in the Murta Formation in Inland–1 could have come from any source, but oil in the Hutton and a residual column in the Poolowanna could only have come from the Poolowanna or older.

Several publications suggest that oil generation and migration in the Cooper-Eromanga basins predates the Tertiary inversion. Nevertheless the distribution of live and residual columns at Morney and Inland (Figs 12, 13, 15) indicate that the oil migrated into the structures after they reached their present configuration (although the Morney oil was lost by minor fault breach). This suggests that either the oil has been re-migrated from an old closure down dip or that a small amount of generation is continuing to the present day. Although modelling of wells on structural highs indicates that the maturation if source rocks became frozen by the erosion and cooling, modelling of wells in areas of minor stripping such as Tanbar North–1 suggests that some generation continued through the Tertiary. This particularly applies to source rocks in the middle of the oil window where increasing time can continue the maturation process even if there is no increase in temperature. Either way, the Inland experience suggests that exploration for young structures is a reasonable proposition, although volumes may not be large.

Acknowledgments

The authors thank the management of Drillsearch Energy Limited for supporting the project and allowing publication. The work was done through MBA Petroleum Consultants (part of the AWT Group) and particular thanks go to Wendy Watkins for the seismic mapping, Wal Muir for useful discussions and the drafting staff (Gavin Hook, Wendy Ronda and Mark Woodger). Two anonymous reviewers made suggestions that substantially improved the document.

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