

# Hydrocarbon migration and mixing in four recently discovered oil fields of the southwestern Eromanga Basin

Catherine Heather Errock (B.Sc)

Organic Geochemistry and Basin Analysis Group

The University of Adelaide

School of Earth and Environmental Sciences

**Supervisor: Assoc. Prof. David McKirdy**

October 2005

# CONTENTS

<b>Abstract</b> .....	3
<b>1. Introduction</b> .....	4
<b>2. Background Geology</b> .....	7
2.1 Stratigraphy.....	7
2.2 Structure .....	8
<b>3. Petroleum Systems</b> .....	9
3.1 Sources and Reservoirs.....	9
3.2 Trapping Mechanisms and Seals .....	10
<b>4. Samples and Analytical Methods</b> .....	11
<b>5. Results and discussion</b> .....	13
5.1 General remarks .....	13
5.2 Thermal maturity and source affinity .....	13
<i>Sellicks Field, Southwestern Patchawarra Trough</i> .....	13
<i>Christies Field, Southwestern Patchawarra Trough</i> .....	14
<i>Arwon and Worrior Fields, Western Wooloo Trough</i> .....	14
5.3 Mixing ratios.....	15
<i>Southwestern Patchawarra Trough</i> .....	15
<i>Western Wooloo Trough</i> .....	15
5.4 Migration .....	16
<i>Southwestern Patchawarra Trough</i> .....	16
<i>Western Wooloo Trough</i> .....	17
5.5 Summary migration models .....	17
<i>Southwest Patchawarra Trough</i> .....	18
<i>Western Wooloo Trough</i> .....	18
<b>Conclusions</b> .....	19
<b>Acknowledgments</b> .....	21
<b>References</b> .....	22
<b>Figure and Table captions</b> .....	25

## **Abstract**

The Cooper and Eromanga Basin is located in northeastern South Australia and southwestern Queensland. Nine samples from four fields within the SA sector of the Cooper-Eromanga Province along the southwestern Patchawarra Trough (Sellicks and Christies) and western Wooloo Trough (Worrior and Arwon) were analysed. The aromatic source and maturity cross-plot of 1-MP/9-MP *versus* 2-MP/1-MP was used to determine the ratio of mixing between Permian- and Jurassic/Cretaceous-sourced hydrocarbon in oils. These oils from the Patchawarra Formation within the Sellicks Field has ~0.9% Rc and is a Family 2 Permian end-member, which has migrated a *minimum* distance of 23-24 km. This same oil contributes 60-70% of the input to the Birkhead and Hutton reservoirs in the Christies Field. The Jurassic input (~0.6% Rc) came from a Birkhead source located 15-30 km to the east.

The Worrior and Arwon Fields contain mixed oils within Jurassic and Cretaceous reservoirs. Here the Permian input decreases up section (Hutton 70%, Birkhead 65%, McKinlay 60%) with the Permian Toolachee Formation and Jurassic Birkhead Formation being the likely source rocks. The *minimum* migration distance for the oil sourced within the Birkhead Formation is 4-5 km from the west and ~24 km from the east.

## 1. Introduction

The accumulation and mixing of oils within the Cooper and Eromanga Basins has been a subject of constant debate over the last 15-20 years. During this time, numerous methods have been developed to allow estimation of the ratio of Cooper-sourced Permian oil to Eromanga-sourced Jurassic/Cretaceous oil in any given reservoir. This information is of some importance for future exploration, given the presence of stacked reservoirs and multiple source rocks within both basins (Alexander, 1996).

Heath et al. (1989) were early advocates of a Permian-only source for the oil reservoirs within sandstone reservoirs of the Eromanga Basin. However, subsequent research has identified many intra-Eromanga oil pools of Jurassic or mixed Jurassic/Permian origin. One of the first attempts to determine the degree of mixing within these reservoirs was that of Jenkins (1989). Using the relative abundances of 25, 28, 30-trisnorhopane and 19-norisopimarane, thought to be age-dependent biomarkers capable of distinguishing oils from the Cooper and Eromanga Basins, he estimated that Eromanga sourced hydrocarbons accounted for up to 40% of the total oil reserves of the two basins. However, Tupper and Burckhardt (1990), Alexander et al (1996) and Michaelsen and McKirdy (2001) questioned this method for two reasons: the biomarkers in question are not specific to the Eromanga Basin; and relative, rather than absolute biomarker concentrations, were employed.

Another approach to the problem of oil mixing involves the use of *n*-alkane carbon isotopic profiles of crude oils and mass balance equations. The *n*-alkanes are a major structural class of compounds found within an unaltered oil sample. Differences in the slopes and isotopic ranges of the profiles reflect different source rocks. Using this method, Boreham and Summons (1999) estimated an Eromanga contribution of 25-65%. This method, however, has a major disadvantage in that any 'minor' contributions (<20%) from a different source rock can remain undetected.

Aromatic hydrocarbons have been found to be more reliable and effective in documenting the phenomenon of oil mixing in the Cooper/Eromanga petroleum province in Alexander et al. (1988) demonstrated the potential of aromatic biomarkers of the *Araucariaceae*, a family of conifers that first appeared in the early Jurassic, to distinguish Eromanga- from Cooper-sourced oils. The biomarkers in question are 1,2,5-trimethylnaphthalene (1,2,5-TMN), 1-methylphenanthrene (1-MP), 1,7-dimethylnaphthalene (1,7-DMN) and retene. While mixed oils can be recognised using ratios of these biomarkers to other “non-biomarker” isomers, this approach is incapable of yielding precise mixing ratios. This is because the aromatic hydrocarbons in question are more abundant in Eromanga crudes, leading to over-estimates of the Jurassic (or Cretaceous) contribution (Arouri et al., 2004).

Michaelsen and McKirdy (2001) explored the idea of taking one of the source parameters that Alexander et al. (1988) formulated (viz. 1-MP/9-MP) and relating it to the methylphenanthrene ratio (MPR: 2-MP/1-MP), a maturity parameter developed by Radke et al. (1982). When plotted against each other, these two isomer ratios were shown to reveal the relative contributions of Cooper Basin and Eromanga-sourced hydrocarbons within any Jurassic or Cretaceous oil pool. Michaelsen and McKirdy (op. cit.) produced two mixing curves, one relevant to the Queensland sector of the Cooper/Eromanga province, and the other to the South Australian sector where a second end-member family of Permian oils occurs..

Arouri and McKirdy (2005) further refined the mixing model curve of Michaelsen and McKirdy (2001) by analysing artificial mixtures of two end-member Jurassic and Permian oils from the Cooper and Eromanga Basins. The result is a more precise quantification of the Michaelsen-McKirdy source/maturity cross-plot.

The present study employs the refined mixing model of Arouri and McKirdy (2005) to determine the source affinity, thermal maturity, migration distance and mixing ratio of nine oils from four recently discovered fields in the southwestern Cooper and Eromanga Basins: two located on the southwestern

flank of the Patchawarra Trough (Christies and Sellicks) and two immediately south of the Warra Ridge in the Wooloo Trough (Worrior and Arwon) (Fig. 1). Both localities allow testing of the “fill and spill” model proposed by Heath et al. (1989) for migration of Permian-sourced hydrocarbons beyond the Cooper Basin zero edge and into traps within the overlying Eromanga Basin.

## **2. Background Geology**

### 2.1 Stratigraphy

The lithostratigraphy of the Permian/Triassic Cooper Basin and the Jurassic/Cretaceous Eromanga Basin is shown in Fig. 2 (after Arouri and McKirdy, 2004). The Merrimelia Formation (Late Carboniferous) and Tirrawarra Sandstone (Early Permian) were deposited in a glacial fluvial system and lie unconformably over the Cambro-Ordovician Warburton Basin. The Tirrawarra Sandstone is a braided fluvial deposit that hosts the major reservoir unit within the Cooper Basin. It is overlain by the coal seams (formed in peat swamp and flood plain facies) of the Patchawarra Formation that are the major source rocks in the Cooper Basin. This formation also contains sandy/silty intervals in which oil and gas are trapped. The Daralingie and Epsilon Formations are fluvial sandstones interbedded with the Murteree and Roseneath Shales. The latter act as regional seals for the hydrocarbons trapped within the Patchawarra Formation (although the presence of Patchawarra-sourced oils within some Eromanga reservoirs suggests that these seals are not everywhere effective: Michaelsen and McKirdy, 2001).

The Late Permian Toolachee Formation unconformably overlies the Daralingie Formation and is of meandering fluvial/ deltaic origin. Its inter-bedded coals comprise another important source rock facies. The Triassic Arrabury and Tinchoo Formations are the youngest sediments within the Cooper Basin succession and consist of shales and siltstones deposited in a meandering stream and flood-plain environment. These fine-grained clastics act as regional seals for the underlying Cooper Basin reservoirs (Hill and Gravestock, 1995).

The hydrocarbon-bearing part of the Eromanga Basin comprises two distinct Early Cretaceous facies associations: lower non-marine and upper marine (Fig. 3). In the Cooper Basin region, the lower non-marine sequence includes the inter-tonguing braided fluvial Hutton and Namur Sandstones; lacustrine shore face sandstones of the McKinlay Member; and the meandering fluvial

overbank and lacustrine facies of the Poolowanna, Birkhead and Murta Formations

The upper prospective part of the Eromanga succession comprises the marginal marine Cadna-Owie Formation overlain by the open marine transgressive and regressive sequences of the Bulldog Shale and Wallumbilla Formations. The Late Cretaceous non-marine units of the Eromanga Basin are not oil producing.

## 2.2 Structure

The structure of the Cooper and Eromanga Basins is dominated by a series of prominent ridges and troughs (Fig. 2). These structural features determine the locations of hydrocarbon kitchens (troughs) and possible pathways of migration into suitable reservoirs and traps (along or adjacent to ridges).

The major structural lows are the Patchawarra and Nappamerri Troughs (Fig. 2). These two features are important depocentres for source rocks. There are also numerous smaller troughs situated throughout the area, including the Wooloo Trough, the site of the Arwon and Worrior Fields.

Separating the Patchawarra and Nappamerri Troughs are the Gidgealpa, Merrimelia, Packsaddle and Innamincka Ridges. These form an arcuate, northeast trending ridge complex known as the GMI Ridge. Along the southern edge of the Wooloo Trough there are two symmetrical, flat-topped features known as the Dunoon and Murteree Ridges from which Permian and Triassic sediments have been stripped by erosion. Here Jurassic Eromanga Basin sediments sit directly on the Cambro-Ordovician sequence of the Warburton Basin (Gravestock and Jensen-Schmidt, 1998)



### **3. Petroleum Systems**

#### 3.1 Sources and Reservoirs

The major source and reservoir units within the Cooper/Eromanga succession are highlighted in Fig. 3. The Patchawarra Formation is the major source rock within the Cooper Basin. Coals and carbonaceous shales up to 60 meters in thickness are inter-bedded with fluvial sands, allowing for effective primary migration of both oil and gas into carrier beds (Kramer et al., 2001). A similar although less prolific Permian source rock is the Toolachee Formation (Boreham and Summons, 1999).

The major oil and gas-bearing reservoir within the Cooper Basin is the Tirrawarra Sandstone, which received its hydrocarbon charge from the coals and shales of the overlying Patchawarra Formation. Other productive reservoirs are the intra-formational sands of the Patchawarra and Toolachee Formations.

Within the Eromanga Basin, the major source rock unit is the mid-Jurassic Birkhead Formation. Its coals and carbonaceous shales have excellent oil-source potential (Michaelsen and McKirdy, 1996). Two other important source units within the basin are the Poolowanna and Murta Formations. The lacustrine Murta Formation is the youngest organic-rich unit that is capable of any form of hydrocarbon generation. It is the most dominant oil source rock along the Murteree Ridge (Michaelsen and McKirdy, 1989; Powell et al., 1989).

Reservoirs within the Eromanga Basin occur throughout the sequence between the Poolowanna and Murta Formations. Of these, the Hutton Sandstone is the most productive, with the Namur Sandstone and McKinlay Members also being effective oil producers, most notably along the Murteree Ridge (Arouri et al., 2004).

### 3.2 Trapping Mechanisms and Seals

The major traps of the Cooper Basin are anticlinal and faulted anticlinal structures. Both have proved to be reliable exploration targets.

Intra-formational shales and coals (also the source facies) form the seals within the major reservoir units of the Tirrawarra Sandstone and the Patchawarra and Toolachee Formations. The Permian Murteree and Roseneath Shales and the fine-grained siliciclastics of the Triassic Arrabury Formation act as regional seals throughout the Cooper Basin.

Hydrocarbon-bearing structures within the Eromanga Basin are mostly anticlines with four-way dip closure, and sandstones draping over pre-existing topographic highs. The seals of the Eromanga Basin consist of intra-formational silts and shales within the Poolowanna, Birkhead and Murta Formations (within the Cooper Basin region). In the Poolowanna Trough, the intra-formational seals of the Poolowanna Formation and siltstones of the Cadna-owie Formation are effective seals. Throughout the rest of the Eromanga Basin, the Cadna-owie Formation, Bulldog Shale and Wallumbilla Formation are effective seals.

Recent exploration along the Cooper Basin zero edge, where the Permo-Triassic sequence pinches out against basement rocks of the Warburton Basin, has been successful in locating oil pools within the Jurassic and Cretaceous sandstones of fields like Christies and Worrior.

#### 4. Samples and Analytical Methods

The crude oils selected for analysis are listed in Table 1, along with their well locations, host formations, producing intervals, flow rates and bulk physical and chemical properties. In PEL 92, operated by Beach Petroleum in the SW Patchawarra Trough, two light paraffinic oils (55-57° API) were recovered from different sands within the Permian Patchawarra reservoir of the Sellicks Field (Fig. 1). These are compared with the heavier (44-45° API) crudes from the Jurassic Birkhead and Namur reservoirs in the Christies Field located some 11 km to the WSW, just beyond the edge of the Cooper Basin.

In PEL 93, operated by Stuart Petroleum in the Wooloo Trough, minor condensate (52° API) was recovered from the Patchawarra reservoir in the Worrior Field (Fig. 1). Oils of similar density flowed on drill stem test from the Jurassic Hutton (53° API) and Birkhead (52° API) reservoirs in the same field; and with two slightly heavier oils (48° API) produced from the Cretaceous McKinlay Member (Murta Formation) at Worrior and the nearby Arwon Field in adjacent PEL 113 (Fig. 1). Since aromatic hydrocarbons comprised only 0.11 wt % of the C<sub>12+</sub> fraction of the Worrior-1 (Patchawarra) condensate (Table 2), and on the reasonable assumption that any Permian charge which reached these intra-Eromanga reservoirs most likely would have originated in the Toolachee Formation (see below), their oils instead were compared with Permian condensate (48-49° API) from the Strzelecki Field, located some 75 km to the ENE on the southern margin of the Nappamerri Trough (Kramer et al., 2004).

In the case of the darker oils in Table 1 (n = 6), asphaltenes were first removed by flooding an aliquot (3 g) with excess petroleum ether (90 ml) and refluxing for 2 hours in a Soxhlet apparatus. Upon cooling, the suspension was filtered through a Whatman No. 42 filter paper to recover the asphaltenes. After rotary evaporation to remove the solvent, the asphaltene-free (or C<sub>12+</sub> maltene) fraction of the oil was ready for column chromatography.

Open-column liquid chromatography (LC) was performed using activated silica topped by activated alumina. The saturated hydrocarbons were eluted first with petroleum ether (80 mL), followed by the aromatic hydrocarbons with petroleum ether and dichloromethane (DCM: 32:48 mL), and finally the resins with DCM and methanol (28:52 mL). Most of the solvent was removed from each fraction using a rotary evaporator before its transfer to a weighed vial for evaporation of the remaining solvent under a capillary stream of N<sub>2</sub>.

The aromatic fractions were submitted to Geotechnical Services Pty Ltd, Welshpool, WA for analysis by gas chromatography-mass spectrometry (GC-MS) in SIM mode using a HP 6890 GC fitted with a ZB-5 column (60m x 0.25 mm i.d. x 0.25 μm film thickness) and interfaced to a HP 5973 mass selective detector. Inlet conditions: pulsed splitless injection at 50 psi; injector temperature, 250°C. Oven conditions: 50-300°C at 3°/min. The following ions were monitored: *m/z* 170 (trimethylnaphthalenes), *m/z* 178 (phenanthrene), *m/z* 192 (methylphenanthrenes), *m/z* 206 (dimethylphenanthrenes) and *m/z* 219 (retene). The data were processed using the HP Chemstation software, allowing peaks to be integrated and molecular parameters calculated. The thermal maturity of each of the oils, expressed as calculated vitrinite reflectance (%R<sub>c</sub>), was determined using Radke and Welte's (1983) calibration of the methylphenanthrene index (MPI-1).

## 5. Results and discussion

### 5.1 General remarks

The C<sub>12+</sub> bulk compositions of the oils as determined by deasphalting and LC are summarised in Table 2. Saturates contents are typically lower for the Permian oils and condensate (26-60% w/w) than for the oils from Jurassic and Cretaceous reservoirs (41-83%). Aromatic hydrocarbons comprise 2-12%, except in the atypical Worrior-1 (DST 4, Patchawarra) condensate, which therefore was excluded from further analysis. Examples of the selected ion chromatograms of the aromatic hydrocarbons used to characterise the maturity and source affinity of these oils are shown in Figs 4 and 5. Aromatic source and maturity parameters, the primary focus of this study, are presented in Tables 3 and 4, along with the equivalent data on the Strzelecki-10 (Toolachee) condensate (Kramer et al., 2004) and the end-member Patchawarra and Birkhead oils from the Moorari Field in the central Patchawarra Trough analysed by Arouri and McKirdy (2005). Fig. 6 comprises a set of source affinity cross-plots based on the Araucariacean biomarker ratios of Alexander et al. (1988), whereas Fig. 7 illustrates the position of the six Eromanga-hosted oils from the Christies, Worrior and Arwon Fields on mixing curves derived from the source-maturity cross-plot of Michaelsen and McKirdy (2001), as re-calibrated by Arouri and McKirdy (2005).

### 5.2 Thermal maturity and source affinity

#### *Sellicks Field, Southwestern Patchawarra Trough*

Not surprisingly, given that they come from adjacent sands in the Patchawarra Formation, the two Permian oils recovered from Sellicks-1 have the same maturity (0.87-0.88% Rc). This is important because it signifies that they belong to Family 2, the second of the two Permian oil types identified by Michaelsen and McKirdy (2001) in the Cooper Basin. Both Sellicks-1 (Patchawarra) oils plot within or near the lower left quadrant of the source affinity diagrams (Fig. 6a,c), confirming their intra-Permian origin as first

proposed by Altman and Gordon (2004). However, it is worth noting that they plot well away from the Moorari-4 (Tirrawarra) crude, which is a typical Family 1 oil.

The latter oil was used as an end-member Permian oil by Michaelsen and McKirdy (2001) and Arouri and McKirdy (2004) when defining their mixing curves. However, the Sellicks-1 (Patchawarra) oil obviously is a more appropriate Permian end-member when determining the mixing ratios of the oils in the stacked Eromanga reservoirs up-dip in the Christies Field (see below).

#### *Christies Field, Southwestern Patchawarra Trough*

Here oil is produced from two Jurassic reservoirs. Oil in the Birkhead at Christies-1 (0.61% Rc) is slightly less mature than that in the overlying Namur at Christies-2 (0.65% Rc), and both are appreciably less mature than the oil in the Patchawarra reservoir of the Sellicks Field.

Inspection of the two source affinity diagrams (Fig. 6a,c) reveals that the Birkhead and Namur crudes plot within or near the upper right quadrant consistent with an origin (at least in part) from source rocks of Jurassic or Cretaceous age, based on the Araucariacean biomarker criteria of Alexander et al. (1988). However, they lie between the end-member Birkhead oil from Moorari-1 and the Patchawarra oils from Sellicks-1. This is significant because it suggests that they may be mixtures of Cooper and Eromanga-sourced hydrocarbons, and not entirely derived from the Patchawarra Formation as claimed by Altman and Gordon (2004).

#### *Arwon and Worrior Fields, Western Wooloo Trough*

Oils pooled in the Cretaceous McKinlay Member at Arwon-1 and Worrior-1 have maturities of 0.62 and 0.63% Rc, respectively. As such they are slightly less mature than those in the underlying Jurassic Birkhead and Hutton reservoirs of the Worrior Field (both 0.67% Rc). The relative abundances of

their Araucariacean biomarkers denote a Jurassic or Cretaceous origin for all these oils (Fig. 6b,d). However, in both source affinity cross-plots, it is worth noting that the proximity of the oil to the Permian quadrant is inversely related to the age of its reservoir. In other words, the extent of a Permian contribution to these oil pools is likely to be Hutton > Birkhead > McKinlay. The observed maturity and source affinity of the oils within the McKinlay Member at Arwon-1 and Worrior-1 could mean one of two things: their hydrocarbons could have (1) been derived from marginally mature source beds in the overlying Murta Formation (Michaelson and McKirdy, 1989; Powell et al., 1999) and migrated down into the McKinlay reservoir, or (2) represent an early charge that was displaced upwards from the underlying Birkhead and/or Hutton reservoirs.

### 5.3 Mixing ratios

#### *Southwestern Patchawarra Trough*

Although their Araucariacean biomarker signatures indicate that the Birkhead and Namur oils in the Christies Field are of post-Permian (probably Jurassic) origin (Fig. 6a,c), the 2-MP/1-MP *versus* 1-MP/9-MP cross-plot (Fig. 7a) reveals that they are mixtures of Permian and Jurassic oil. In fact, approximately 60% of the Birkhead oil and 70% of the Namur oil is of Permian origin. This Permian contribution most likely originated from oil-prone coals of the Patchawarra Formation in a hydrocarbon kitchen some 18-21 km to the east (Fig. 8a). The inferred location of the kitchen is based on the assumption that the Permian oil is of the same source affinity and maturity as the Family 2 crude trapped in the Patchawarra reservoir at Sellicks-1.

#### *Western Wooloo Trough*

A similar oil-mixing scenario is apparent in the Eromanga reservoirs at Arwon-1 and Worrior-1 (Fig. 7b). Here the Permian contribution (in this case from coals of the Toolachee Formation) increases from approximately 60% in the McKinlay, through 65% in the Birkhead, to 70% in the Hutton.

## 5.4 Migration

Oil maturities based on MPI-1 and expressed as equivalent vitrinite reflectance of the source rock at the time of primary migration (Rc %: Table 3), in conjunction with isoreflectance maps for the two principal source rock units (Fig. 8a,b), allow delineation of hydrocarbon kitchens and likely migration pathways.

### *Southwestern Patchawarra Trough*

Oil pooled within the Patchawarra Formation at Sellicks-1 is of Permian source-affinity and hence most likely was generated and expelled from intra-formational coal. The oil's maturity (0.87-0.88% Rc) is greater than that of coal in the host reservoir (~0.76% Ro: Fig. 8a), showing that it is clearly out of place.

For the Sellicks Field, the hydrocarbon kitchen is located to the west of the trap, and its oil has migrated at least 10 km up dip to its current location (Fig. 8a). This is only a *minimum* migration distance because the oil could have originated from further away when coals, now of higher maturity (or rank), were less deeply buried.

Because Permian oil has mixed with indigenous Jurassic oil in the Eromanga reservoirs of the Christies Field, we can infer that oil from the same hydrocarbon kitchen has continued migration along the same pathway. For this oil, a minimum migration distance of 23-24 km is indicated.

The Eromanga input in to the Birkhead and Namur oil pools of the Christies Field is presumed to have come from the dominant Jurassic (intra-Birkhead) source rock. Thus, again, the calculated maturities of these two oils (0.61-0.65% Rc: Table 3) and the isoreflectance map of the Birkhead Formation (Fig. 8b) can be used to determine how far the Jurassic oil charge has migrated. Because isoreflectance contours typically follow structural trends (higher maturity in deeper areas), two possible migration pathways can be



interpreted (Fig. 8b). The southern route represents a distance of 30-32 km; and the northern route a distance of ~18 km.

#### *Western Wooloo Trough*

No samples were analysed to provide source and maturity information on the condensate from the Patchawarra Formation at Worrior-1. Moreover, since the Permian charge into the Eromanga reservoirs, here and at Arwon-1, is interpreted to have come from coals of the Toolachee Formation within the Wooloo Trough, migration distances cannot be calculated because no isorefectance map was available for this formation. Only the Eromanga (Birkhead-sourced) inputs to the Hutton, Birkhead and McKinlay reservoirs of these fields can be evaluated in terms of their migration distances.

Due to their stratigraphic proximity and identical thermal maturity (0.67% Rc: Table 3), it is likely that the Jurassic component of the Hutton and Birkhead oil pools originated from the same source rock and hydrocarbon kitchen. Two potential kitchen areas are identified in the Birkhead Formation (Fig. 8b). Oil expelled from the western kitchen would have to have migrated only 4-5 km to reach the Jurassic reservoirs of the Worrior Field. Another hydrocarbon kitchen lies to the northeast of Arwon-1. Southwesterly migration from this kitchen of an earlier charge (0.62-0.63% Rc) from this kitchen would have travelled a minimum distance of ~18 km to reach the McKinlay reservoir at Arwon-1, and a further 6 km into the same reservoir at Worrior-1 (i.e. a total distance of ~24 km). Alternatively, the McKinlay reservoir in the Worrior Field could have been charged by Jurassic hydrocarbons that were expelled from local Birkhead source rocks and migrated vertically up one of the faults bounding the Worrior structure (Fig. 10).

#### 5.5 Summary migration models

### *Southwest Patchawarra Trough*

Figure 9 shows a cross section through the Christies and Sellicks Fields. The Permian hydrocarbon kitchen is situated within the deeper sediments of the Patchawarra Formation. Oil expelled from the coal source rock migrated up dip beneath the intra-Patchawarra seal and entered the Hutton-Birkhead sequence past the erosional edge of the seal. The Christies reservoirs are located beyond the Cooper Basin margin. The presence of oil in the Namur Sandstone implies that the Birkhead seal has leaked, allowing migration up section into younger Eromanga reservoirs.

There is, however, a second source rock in the area allowing migration from a Jurassic (probable Birkhead) source into the reservoirs. The Birkhead oil kitchen is situated to the east of the Christies and Sellicks Fields. Its oil migrated westward, underneath the intra-Birkhead seal into the Birkhead and Namur reservoirs at Christies.

### *Western Wooloo Trough*

The E-W seismic section through Worrior-1 and Arwon-1 (Fig. 10), illustrates the stratigraphic constraints on the migration of oil from the Birkhead Formation into the overlying McKinlay Member or downwards into the Hutton Sandstone. Migration into the McKinlay could have occurred from its overlying source rock, the Murta Member. However due to the presence of faults within the Worrior structure, it is more likely that oil reached its McKinlay reservoir by migrating up the fault to the rest of the field. These hydrocarbons could have entered the trap from both the east and the west (Fig. 10).

## Conclusions

1. The maturity of the oil from the Patchawarra Formation at Sellicks-1 (0.87-0.88%Rc) signifies that it belongs to the second of two Permian oil families identified by Michaelsen and McKirdy (2001) within the Cooper Basin. Oils within the Jurassic reservoirs at Christies-1 and -2 are less mature (0.61%Rc, Birkhead and 0.65%Rc, Namur) and are of a mixed Jurassic-Permian source affinity.

2. Oils within the Cretaceous McKinlay Member at Arwon-1 and Worrior-1 have maturities of 0.62 to 0.63%Rc making them less mature than those in the underlying Jurassic Birkhead and Hutton reservoirs at Worrior-1 (0.67%Rc). Again, these Eromanga-hosted oils are of a mixed source affinity

3. The Sellicks Field on the SW flank of the Patchawarra Trough contains Family 2 Permian oil generated from coals within the early Permian Patchawarra Formation. This oil has also migrated into the Birkhead and Namur reservoirs of the Christies Field where it mixed with indigenous Jurassic oil and makes up 60-70% of the total charge.

4. Mixing in Jurassic and Cretaceous reservoirs within the Western Woolloo Trough occurred between Permian oil from the Toolachee Formation and Jurassic oil from the Birkhead Formation, with Permian input increasing up the section (Hutton 70%, Birkhead 65%, McKinlay 60%).

5. Oil from the Patchawarra Trough migrated 10 km up dip into the Sellicks Field and continued along the same pathway into the Birkhead and Namur reservoirs of the Christies Field, a total migration distance of at least 23-24 km. The Eromanga Birkhead input into the Jurassic reservoirs has found two possible migration pathways: a southern route totalling 30-32 km, and a northern route over a distance of ~18 km.

6. The Jurassic component of the Hutton, Birkhead and McKinlay reservoirs of the Arwon and Worrior fields most likely originated in the Birkhead Formation and could have come from two possible source kitchens. Migration from the

kitchen located west of the Worrior structure would have occurred over 4-5km. However, hydrocarbons from the eastern kitchen would have migrated at least 24 km before reaching the Worrior Field.

## **Acknowledgments**

This research project was made possible by the generous financial support of Beach Petroleum Limited.

David McKirdy for his guidance, patience, knowledge and support for making this a rewarding and fun project.

I'd like to thank Janet Skinner (Beach Petroleum) and Maris Zwigulis (Stuart Petroleum) for information and advice during the project, and the management of their companies for the oil samples analysed in this study.

Lynn Webster (OGBA Group, University of Adelaide) provided patient guidance in the laboratory and Geotechnical Services Pty Ltd, WA undertook the GC-MS analysis of the aromatic fractions.

I'd also like to thank Chrissy, Dee, Stacey and DC for allowing me to share with them my love and loyalty for 'great' music. All year. Whether they liked it or not.

And last, but definitely not least all my family, for all their love and support over the last few years.

## References

Alexander, E.M, 1996. Reservoirs and seals In: Alexander, E.M. and Hibburt, J.E. (Eds), The petroleum geology of South Australia. Vol. 2: Eromanga Basin. Department of Mines and Energy South Australia, Report Book 96/20, 141-148.

Alexander, R., Larcher, A.V., Kagi, R.I. and Price, P.L., 1988. The use of plant-derived biomarkers for correlation of oil with source rocks in the Cooper/Eromanga Basin system, Australia. The APEA Journal 28, 310–325.

Altmann, M.J., Gordon, H.M., 2004. Oil on the Patchawarra Flank – some implications from the Sellicks and Christies oil discoveries, Petroleum Exploration Society of Australia, Eastern Australasian Basins Symposium II, Adelaide, September 2004, pp.29-34

Arouri, K.R., McKirdy, D.M., Schwark, L., Leythaeuser, D. and Boulton, P.J., 2004. Accumulation and mixing of hydrocarbons in oil fields along the Murteree Ridge, Eromanga Basin, South Australia. Organic Geochemistry 35, 1597-1618.

Arouri, K.R., McKirdy, D.M., 2005. The behaviour of aromatic hydrocarbons in artificial mixtures of Permian and Jurassic end-member oils: application to in-reservoir mixing in the Eromanga Basin, Australia. Organic Geochemistry 36, 105-115.

Boreham, C.J., Hill, A.J., 1998. Source rock distribution and hydrocarbon geochemistry. In: Gravestock, D.I., Hibburt, J.E. and Drexel, J.F. (Eds), The petroleum geology of South Australia. Vol. 4: Cooper Basin, Department of Primary Industries and Resources South Australia, Report Book 98/9, 131–144.

Boreham, C.J. and Summons, R.E., 1999. New insights into the active petroleum systems in the Cooper and Eromanga Basins, Australia. *The APPEA Journal* 39, 263–296.

Burckhardt, D., 1990. Base Patchawarra Formation and Mid Birkhead Formation (P.E.L. 5 & 6) 1:250 000 Isoreflectance Maps (Santos Ltd)

Gravestock, D.J., Jensen-Schmidt, B., 1996 Structural setting In: Gravestock, D.I., Hibburt, J.E. and Drexel, J.F. (Eds), *The petroleum geology of South Australia. Vol. 4: Cooper Basin.* Department of Primary Industries and Resources South Australia, Report Book 98/9, 157–179.

Heath, R., McIntyre, S., Gibbins, N., 1989. A Permian origin for Jurassic reservoir oil in the Eromanga Basin. In: O’Neil, B.J. (Ed.), *The Cooper and Eromanga Basins, Australia. Proceedings of PESA, SPE, ASEG (SA Branches)*, Adelaide, 405–416.

Hill, A.J., Gravestock, D.I., 1995. Cooper Basin: Structure and Setting. In: Drexel, J.F., Preiss, W.V. (Eds.), *The Geology of South Australia, Vol. 2 The Phanerozoic.* Geological Survey of South Australia, Bulletin 54, pp. 78-87.

Jenkins, C.C., 1989. Geochemical correlations of source rocks and crude oils from the Cooper and Eromanga Basins. In: O’Neil, B.J. (Ed), *The Cooper and Eromanga Basins, Australia. Proceedings of PESA, SPE, ASEG (SA Branches)*, Adelaide, 525–540.

Kramer, L., McKirdy, D.M., Arouri, K.R., Schwark, L., Leythaeuser, D., 2004. Constraints on the hydrocarbon charge history of sandstone reservoirs in the Strzelecki Field, Eromanga Basin, South Australia. *Petroleum Exploration Society of Australia, Eastern Australasian Basins Symposium II*, Adelaide, September 2004

Michaelsen, B.H., McKirdy, D.M., 1989. Organic facies and petroleum geochemistry of the lacustrine Murta Member (Mooga Formation) in the

Eromanga Basin, Australia. In: O'Neil, B.J. (Ed), The Cooper and Eromanga Basins, Australia. Proceedings of Petroleum Exploration Society of Australia, Society of Petroleum Engineers, Australian Society Exploration Geophysicists (SA Branches), Adelaide, pp. 541–558.

Michaelsen, B.H., McKirdy, D.M., 1996. Source rock distribution and hydrocarbon geochemistry. In: Alexander, E.M., Hibburt, J.E. (Eds) The Petroleum Geology of South Australia, vol. 2: Eromanga Basin. Department of Mines and Energy South Australia, Report Book 96/20, 101–110.

Michaelsen, B.H., McKirdy, D.M., 2001. Migration and mixing of oils in the Cooper and Eromanga Basins, Central Australia. In: Hill, K.C. and Bernecker, T. (Eds), Eastern Australasian Basins Symposium, a refocused energy perspective for the future. Petroleum Exploration Society of Australia, Special Publication, pp. 289–300.

Powell, T.G., Boreham, C.J., McKirdy, D.M., Michaelsen, B.H., Summons, R.E., 1989. Petroleum geochemistry of the Murta Member, Mooga Formation and associated oils, Eromanga Basin, Australia. APEA Journal 29 (1), 114–129.

Radke, M., Welte, D.H., 1983. The methylphenanthrene index (MPI): a maturity parameter based on aromatic hydrocarbons. In: Bjørøy, M. et al. (Eds.), Advances in Organic Geochemistry 1981. Wiley, Chichester, pp. 504–512.

Radke, M., Willsch, H., Leythaeuser, D., Teichmüller, M., 1982. Aromatic components of coal: relation of distribution patterns to rank. *Geochimica et Cosmochimica Acta* 46, 1831–1848.

Tupper, N.P., Burckhardt, D.M., 1990. Use of the methylphenanthrene index to characterize expulsion of Cooper and Eromanga Basin oils. APEA Journal 30 (1), 375–385.



## Figure and Table captions

Figure 1. Location of Beach Petroleum's, Sellicks' and Christies Fields and Stuart Petroleum's Worrior and Arwon Fields.

Figure 2. Major structures within the South Australian sector of the Cooper-Eromanga Basin province (from Gravestock and Jensen-Schmitt, 1996)

Figure 3. Lithostratigraphy of the Cooper and Eromanga Basins (adapted from Arouri and McKirdy, 2004) Insets show the locations of the drill stem tests that yielded the oils examined in this study.

Figure 4. SIM mass chromatograms of phenanthrene ( $m/z$  178) and methylphenanthrenes ( $m/z$  192) in selected DST oils: (a,b) Christies-1, Birkhead Fm and (c,d) Sellicks-1, Patchawarra Formation.

Figure 5. SIM mass chromatograms, *trimethylnaphthalenes* ( $m/z$  170), *dimethylphenanthrenes* ( $m/z$  219), of hydrocarbons in selected DST oils (a) Christies-1, Birkhead Fm and (b) Sellicks-1, Patchawarra Formation

Figure 6. Source affinity plots (after Alexander et al., 1988) of selected oils (a, c) Christies and Sellicks Fields and (b, d) Worrior and Arwon Fields.

Figure 7. Cross-plot of 1-MP/9-MP versus 2-MP/1-MP incorporating the calibrated mixing curve from Arouri and McKirdy, (2004): (a) Christies and Sellicks Fields and (b) Worrior and Arwon fields.

Figure 8. Vitrinite isoreflectance maps of the (a) base Patchawarra Formation and (b) mid-Birkhead Formation showing well locations and inferred migration pathways. Maps modified from Burckhardt (1990).

Figure 9. Schematic cross-section through the Patchawarra Trough and the Christies-1 and Sellicks-1 well locations, showing hydrocarbon migration pathways and oil kitchen locations (adapted from Altmann and Gordon, 2002)

Figure 10. Schematic cross-section through the Arwon-1 and Worrior-1 well locations, showing hydrocarbon migration pathways and oil kitchen locations (Arwon Well Completion Report, Stuart Petroleum).

Table 1. Oil sample data and locations for Christies-1 and 2 and Sellicks-1 (Patchawarra Trough), and Worrior-1 and Arwon-1 (Wooloo Trough) taken from well completion reports.

Table 2. C<sub>12+</sub> bulk composition of crude oils as determined by deasphalting (where indicated) and open-column liquid chromatography.

Table 3. Aromatic maturity parameters of crude oils. Data on oils from Strzlecki-10 (Kramer et al., 2004) and Moorari-1 and 4 (Arouri and McKirdy, 2004) included for comparison.

Table 4. Aromatic source parameters of crude oils. Data on oils from Strzlecki-10 (Kramer et al., 2004) and Moorari-1 and -4 (Arouri and McKirdy, 2004) included for comparison.

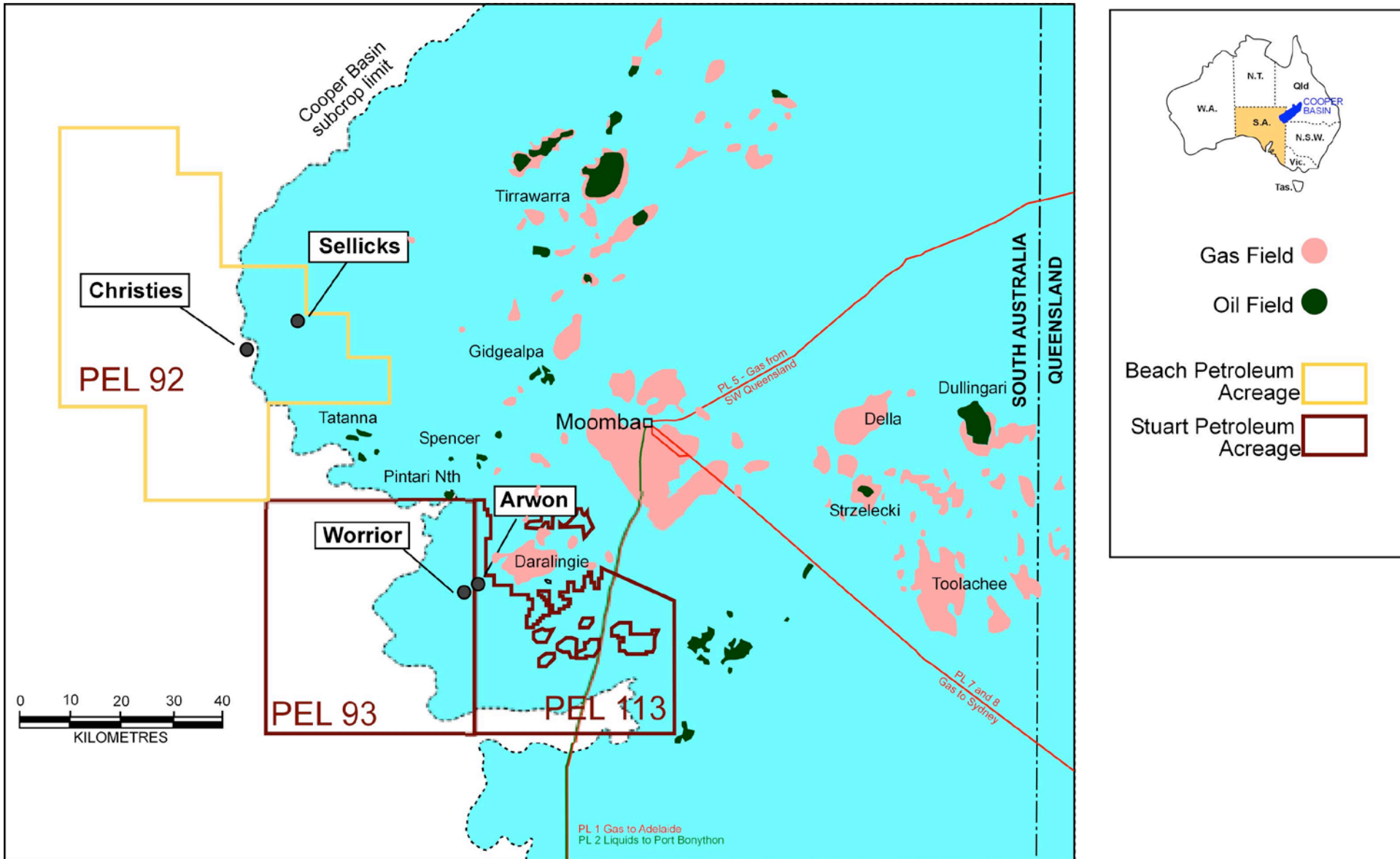


Figure 1

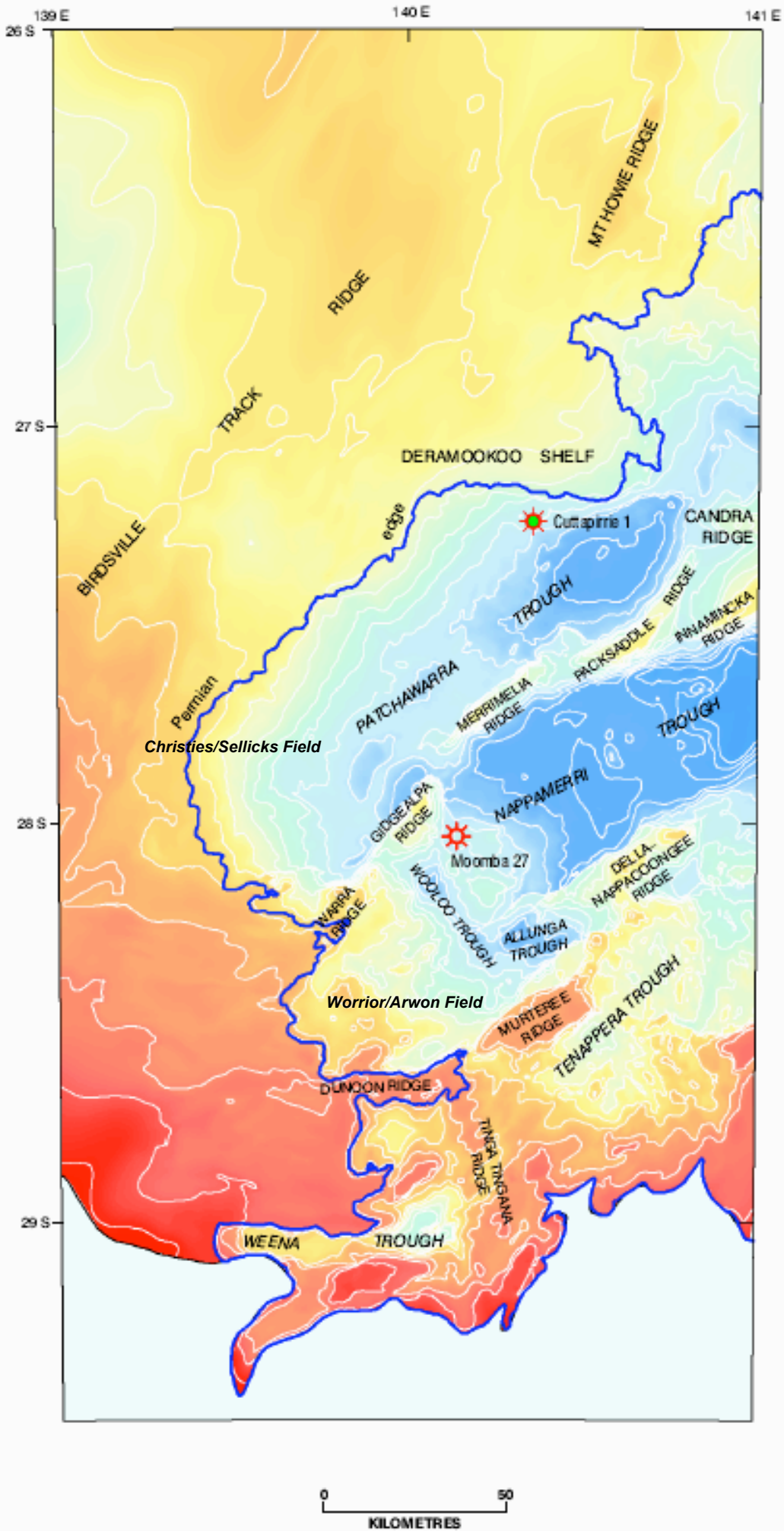


Figure 2

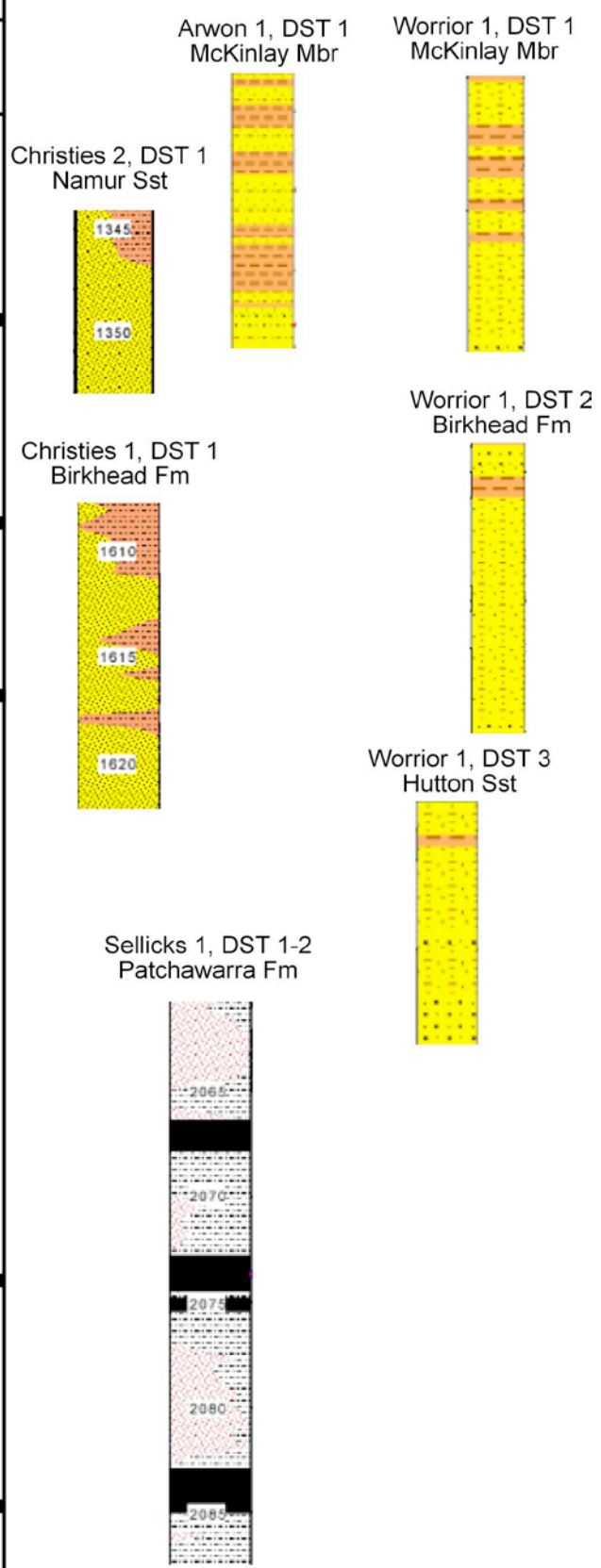
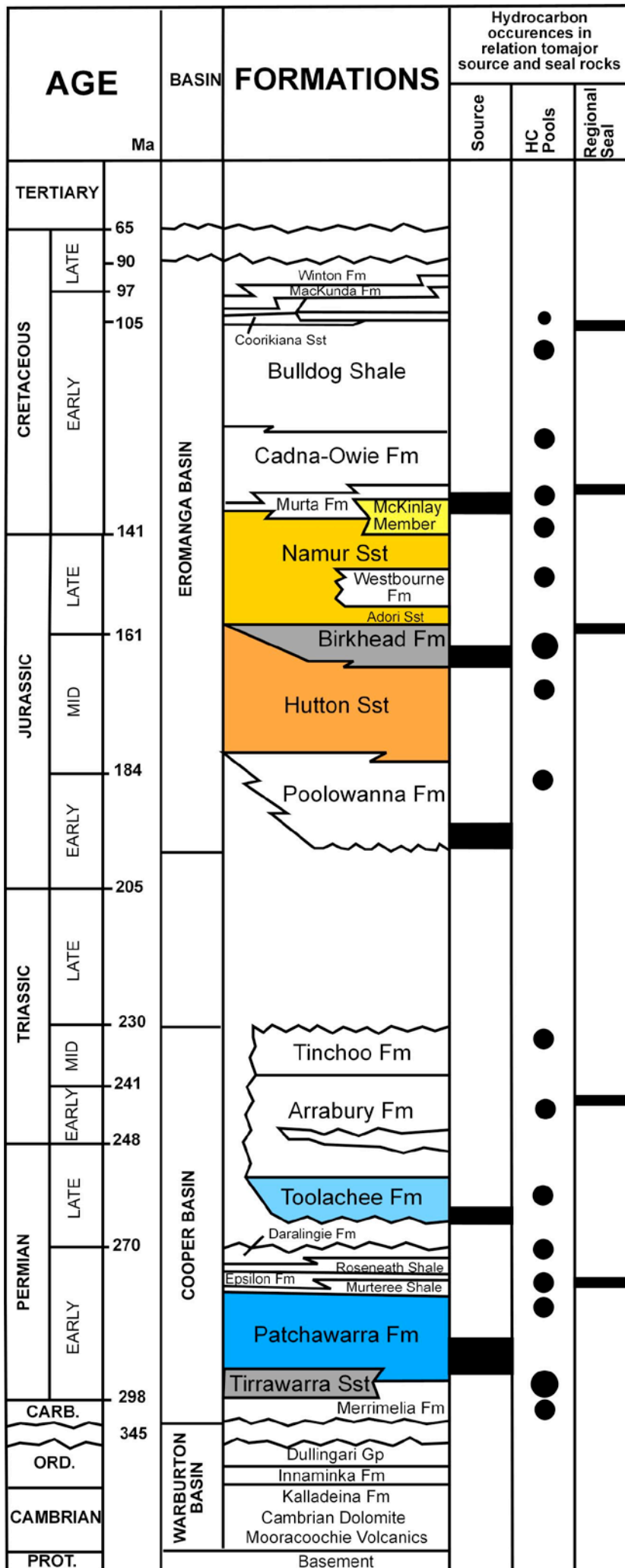


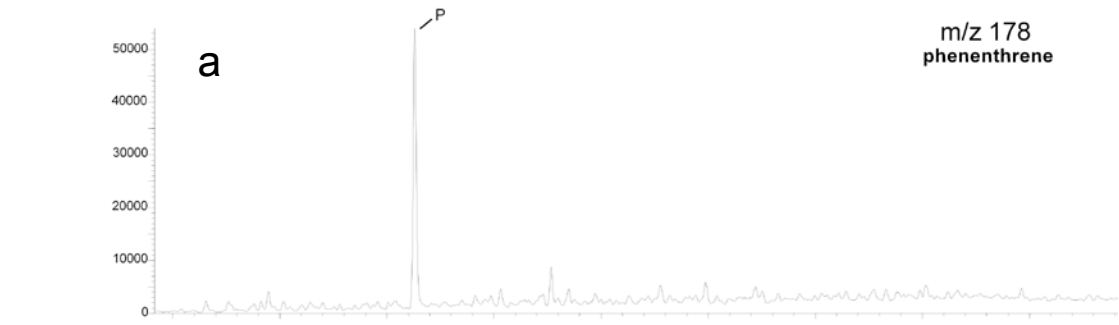
Figure 3

Figure 4

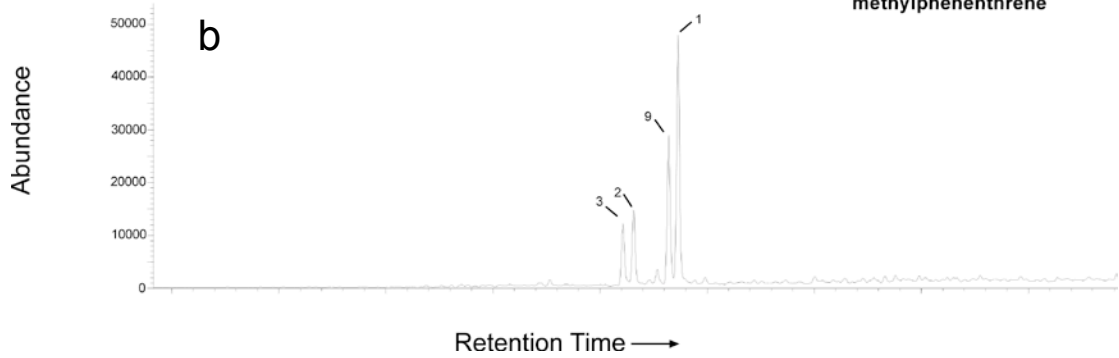
Birkhead Fm - Jurassic

Christies-1 DST-1

*m/z* 178  
phenanthrene



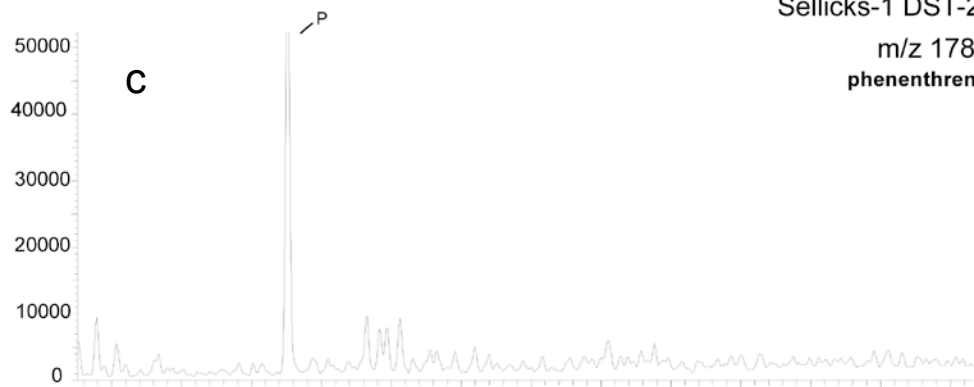
*m/z* 192  
methylphenanthrene



Patchawarra Fm - Permian

Sellicks-1 DST-2

*m/z* 178  
phenanthrene



*m/z* 192  
methylphenanthrene

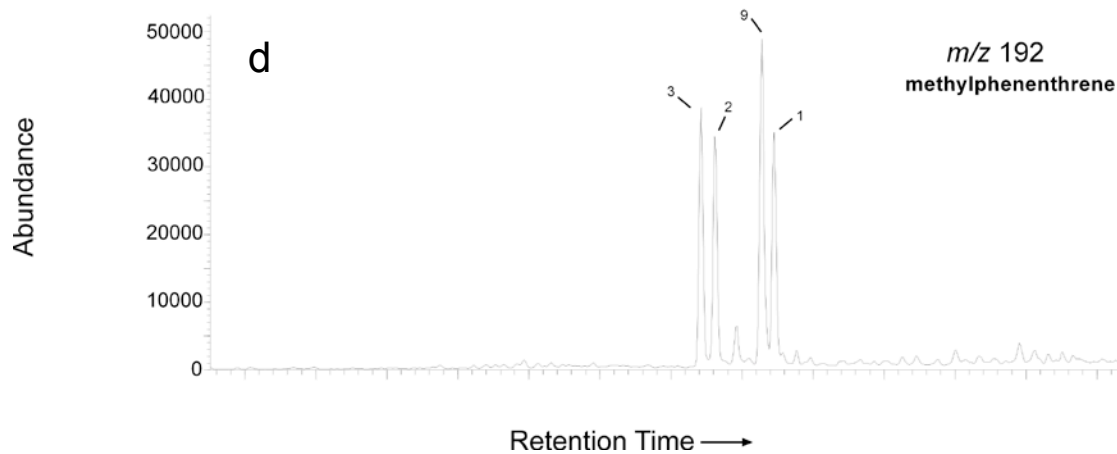


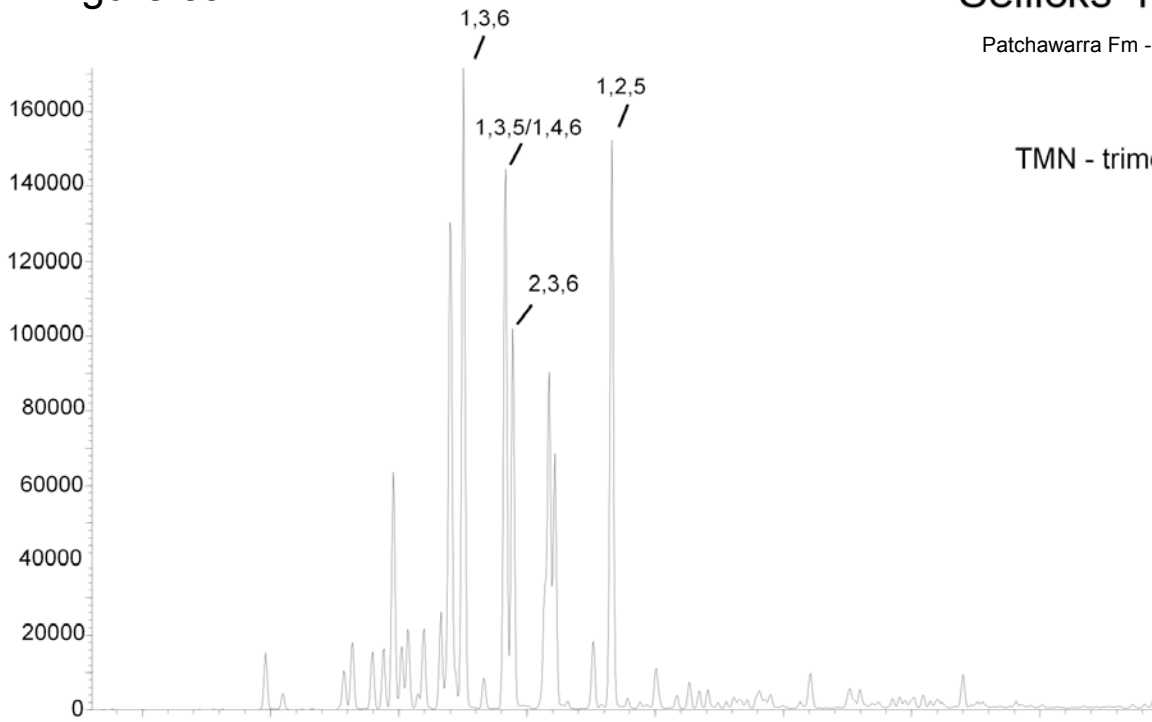
Figure 5a

Sellicks-1 DST-2

Patchawarra Fm - Permian

m/z 170

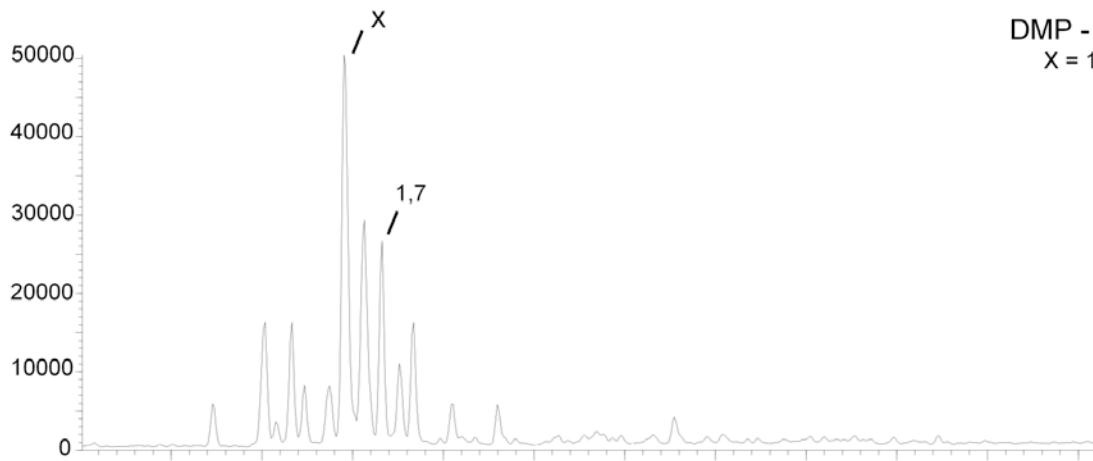
TMN - trimethylnaphthalenes



m/z 206

DMP - dimethylphenanthrene

X = 1,3/2,4/3,9/2,10/3,10 - DMP



m/z 219

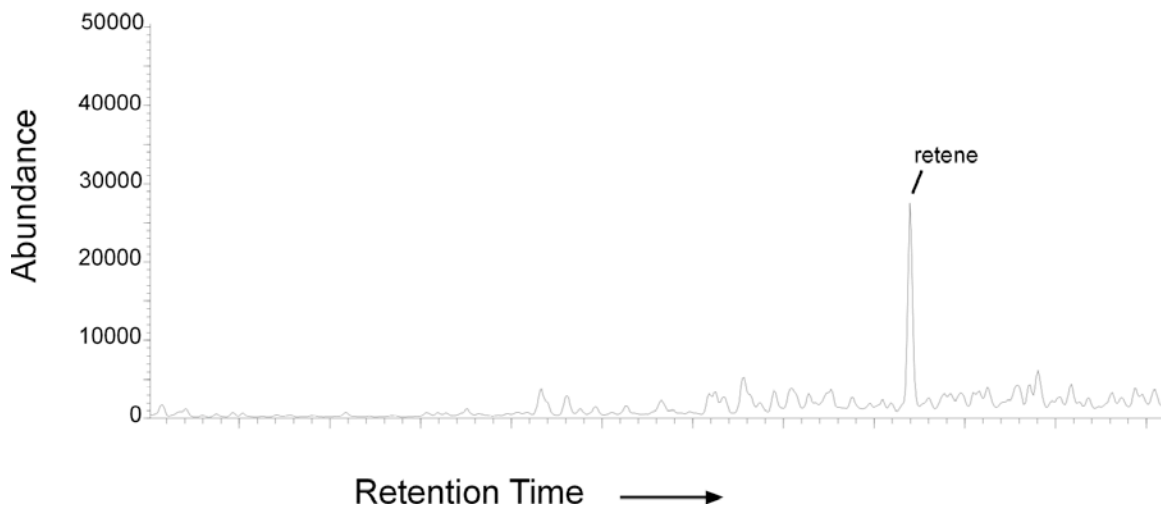


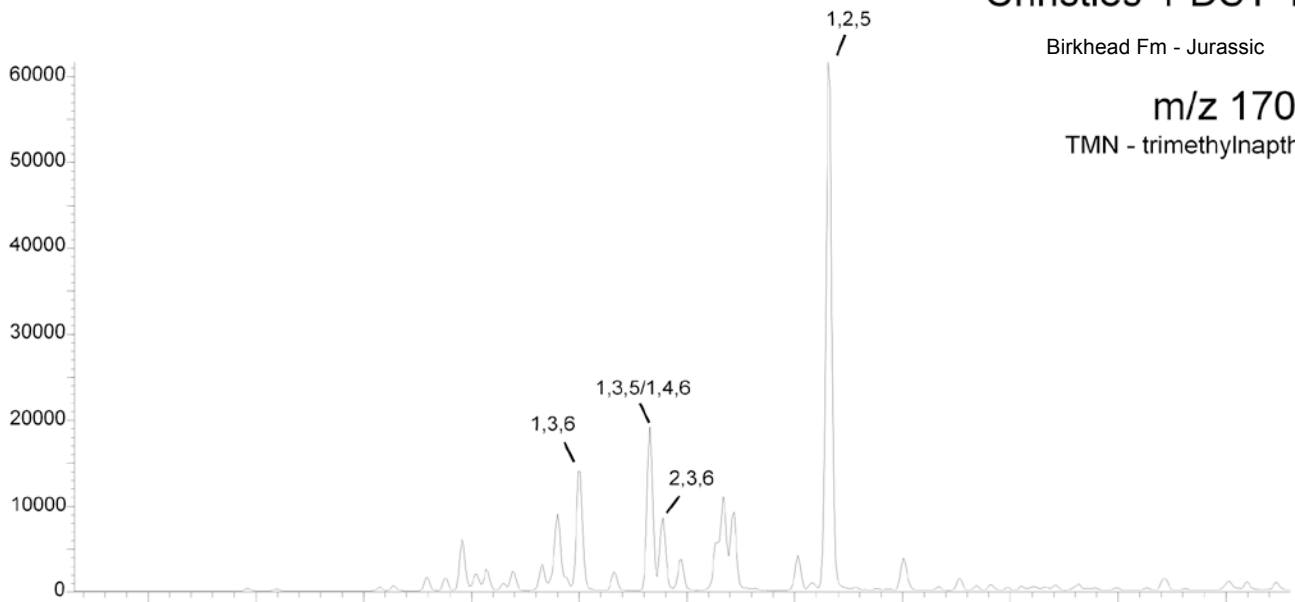
Figure 5b

Christies-1 DST-1

Birkhead Fm - Jurassic

m/z 170

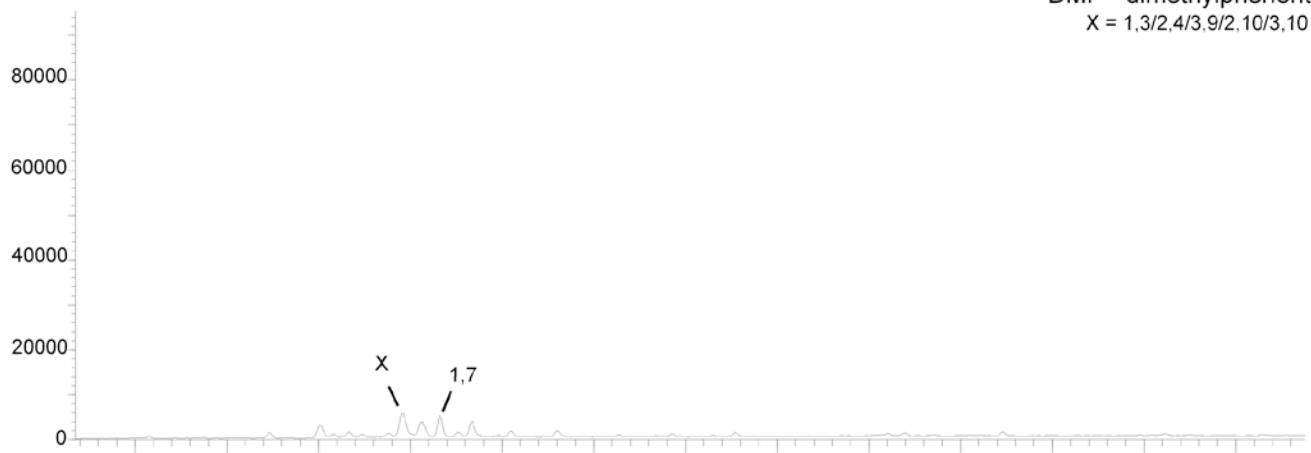
TMN - trimethylnaphthalenes



m/z 206

DMP - dimethylphenanthrenes

X = 1,3/2,4/3,9/2,10/3,10 - DMP



m/z 219



Retention Time →



Figure 6

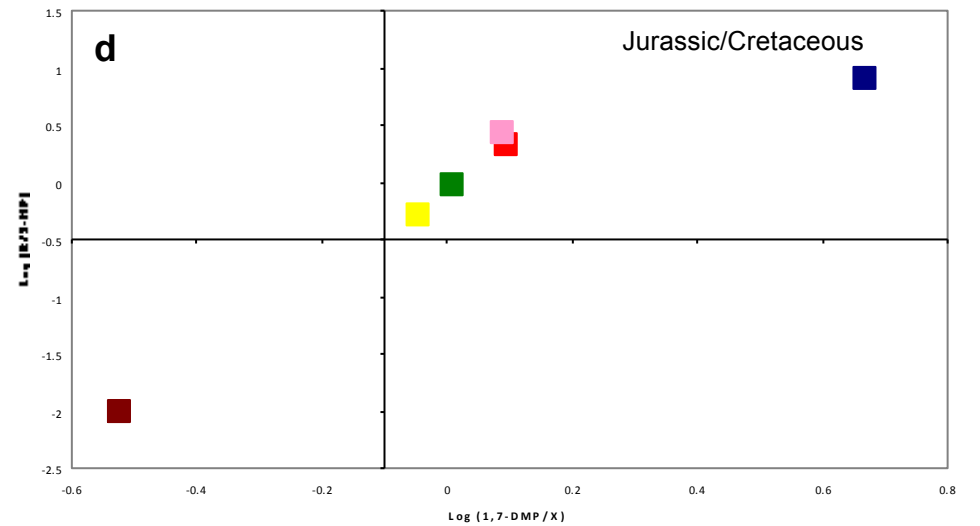
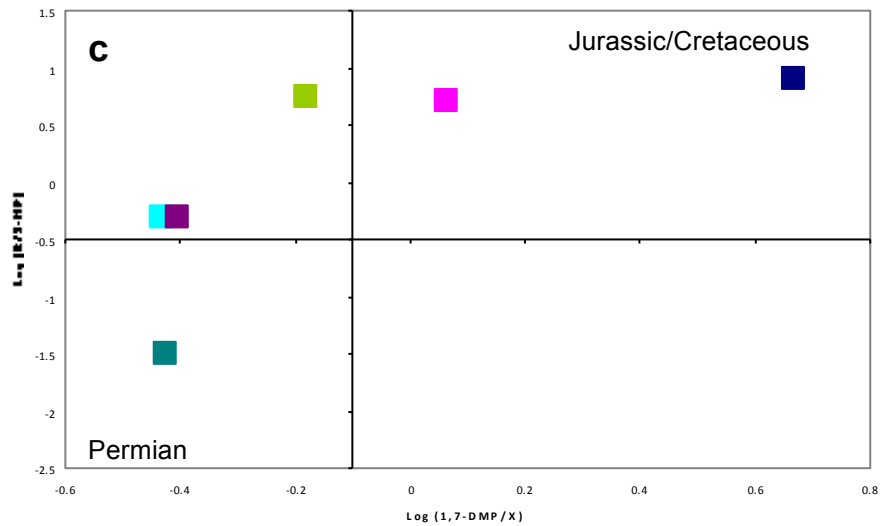
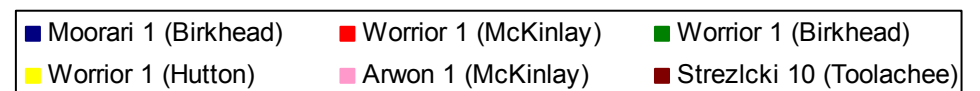
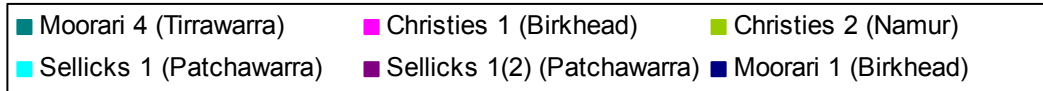
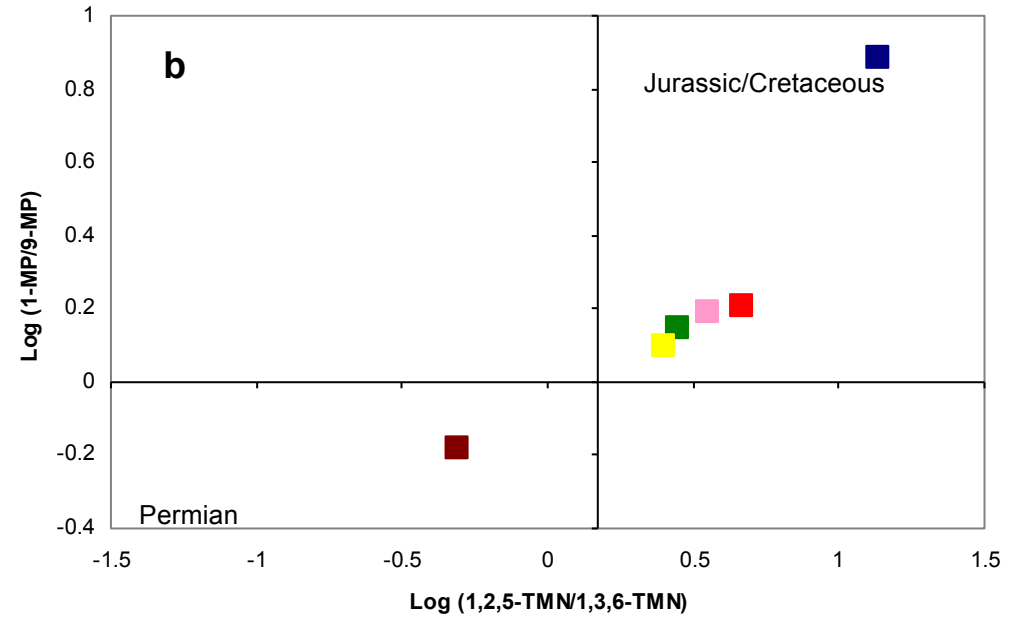
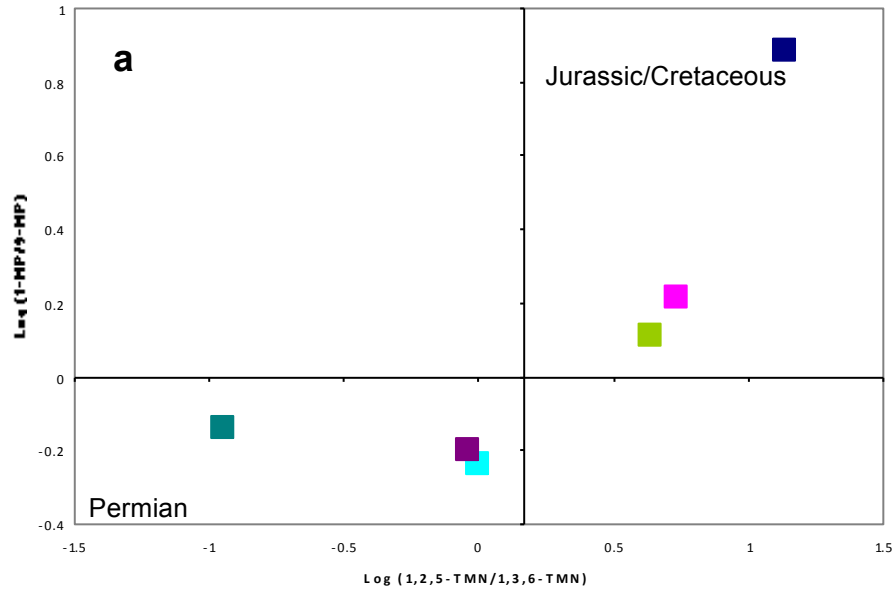
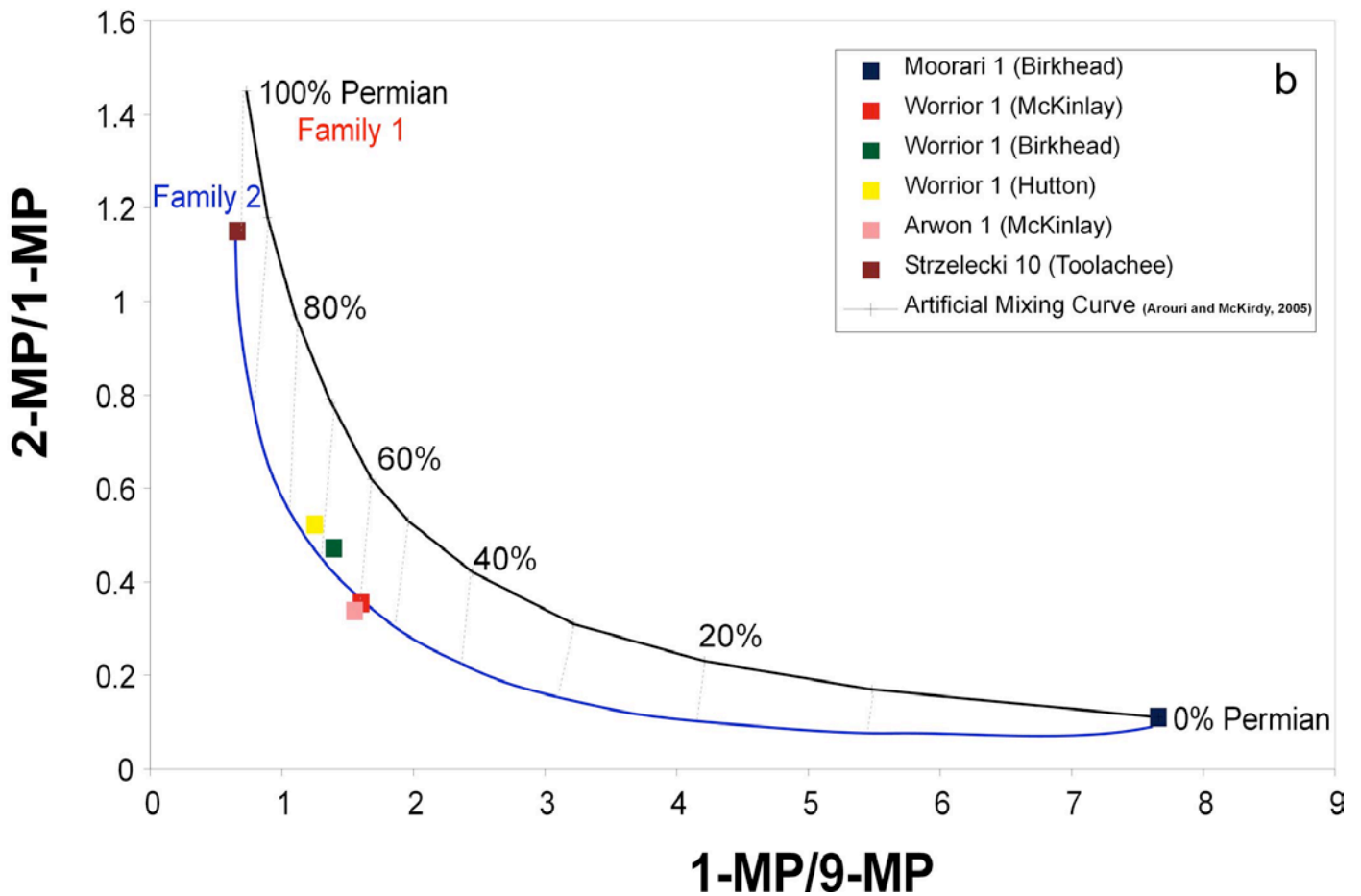
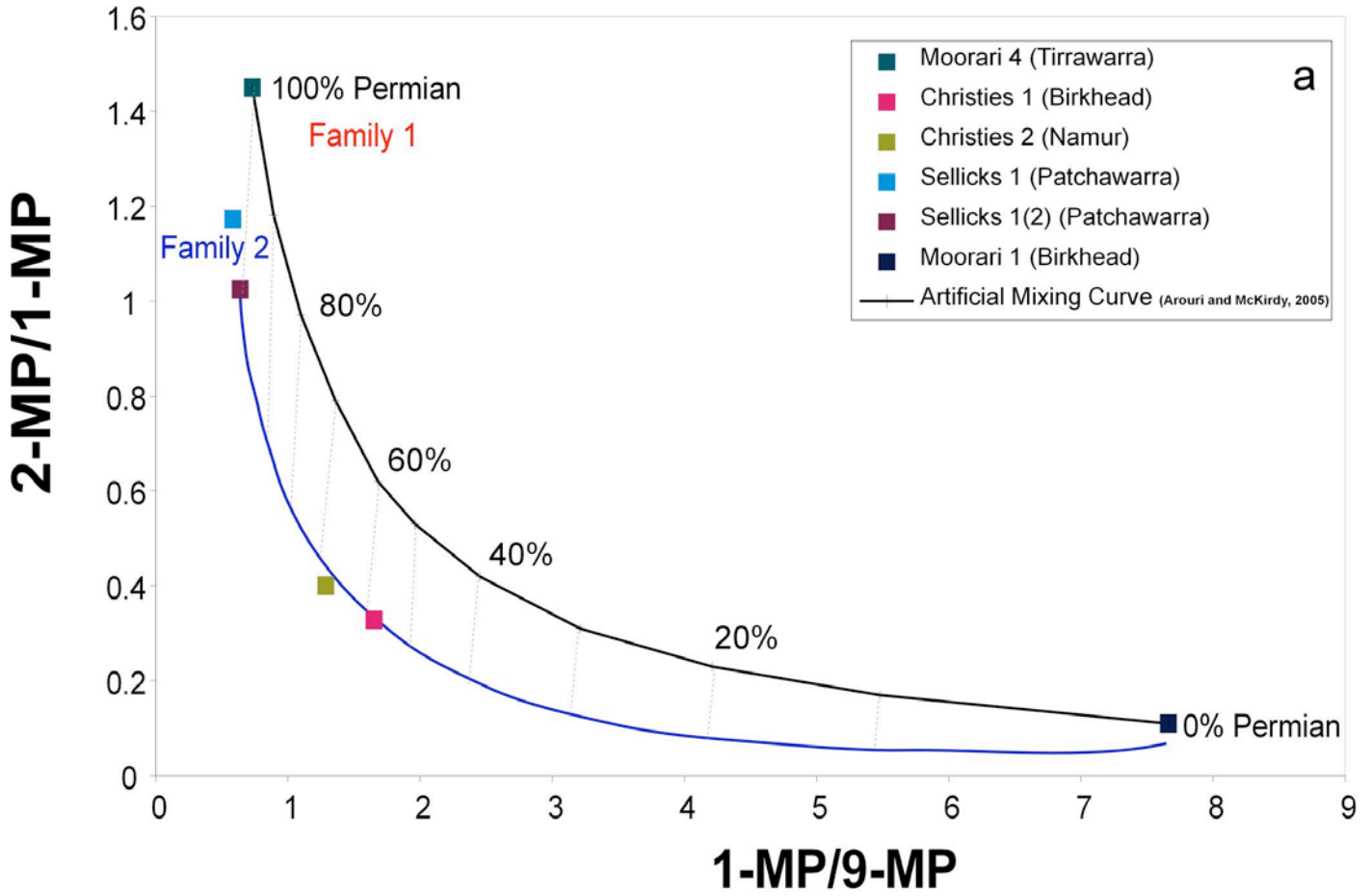


Figure 7



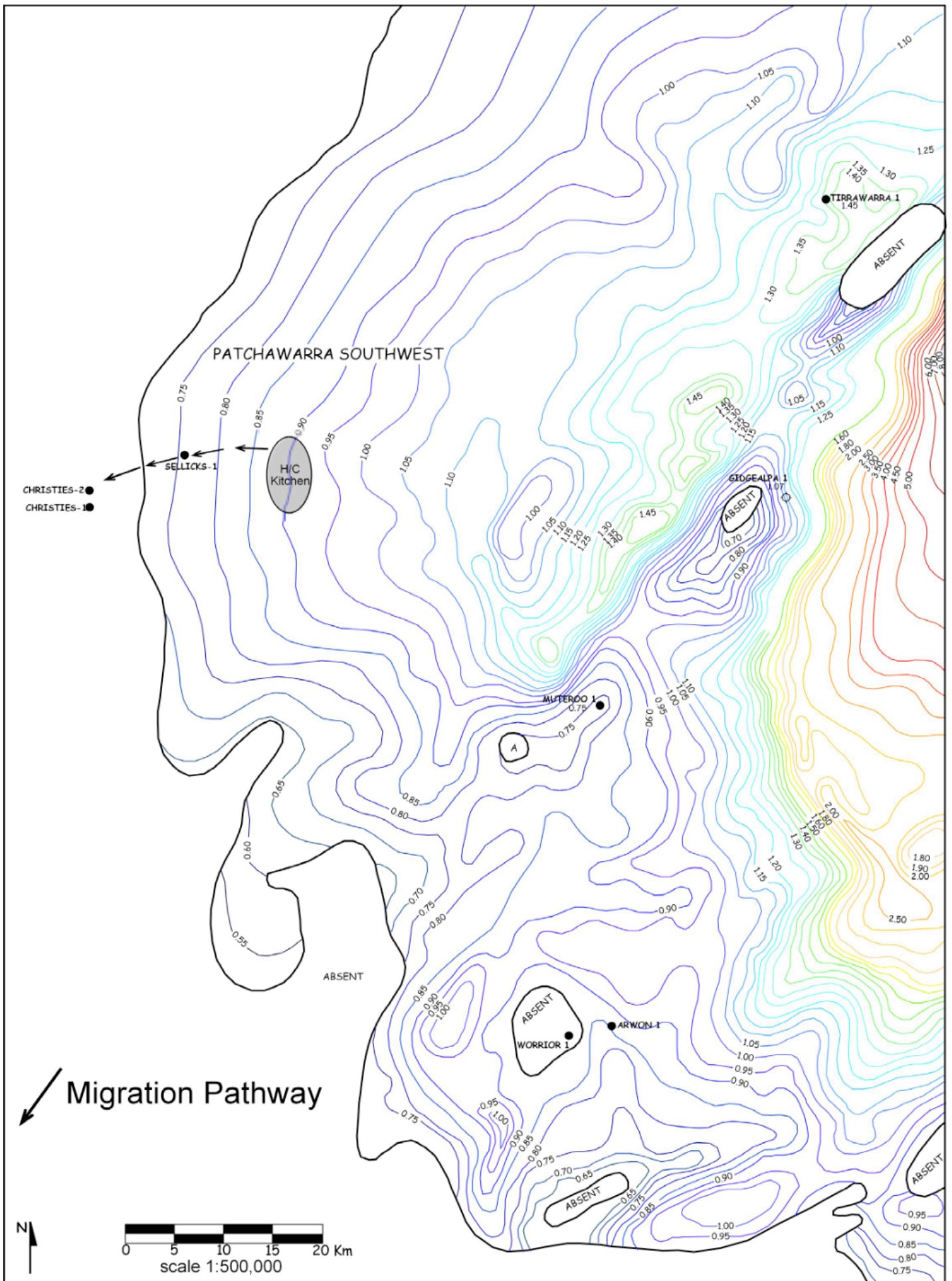


Figure 8a

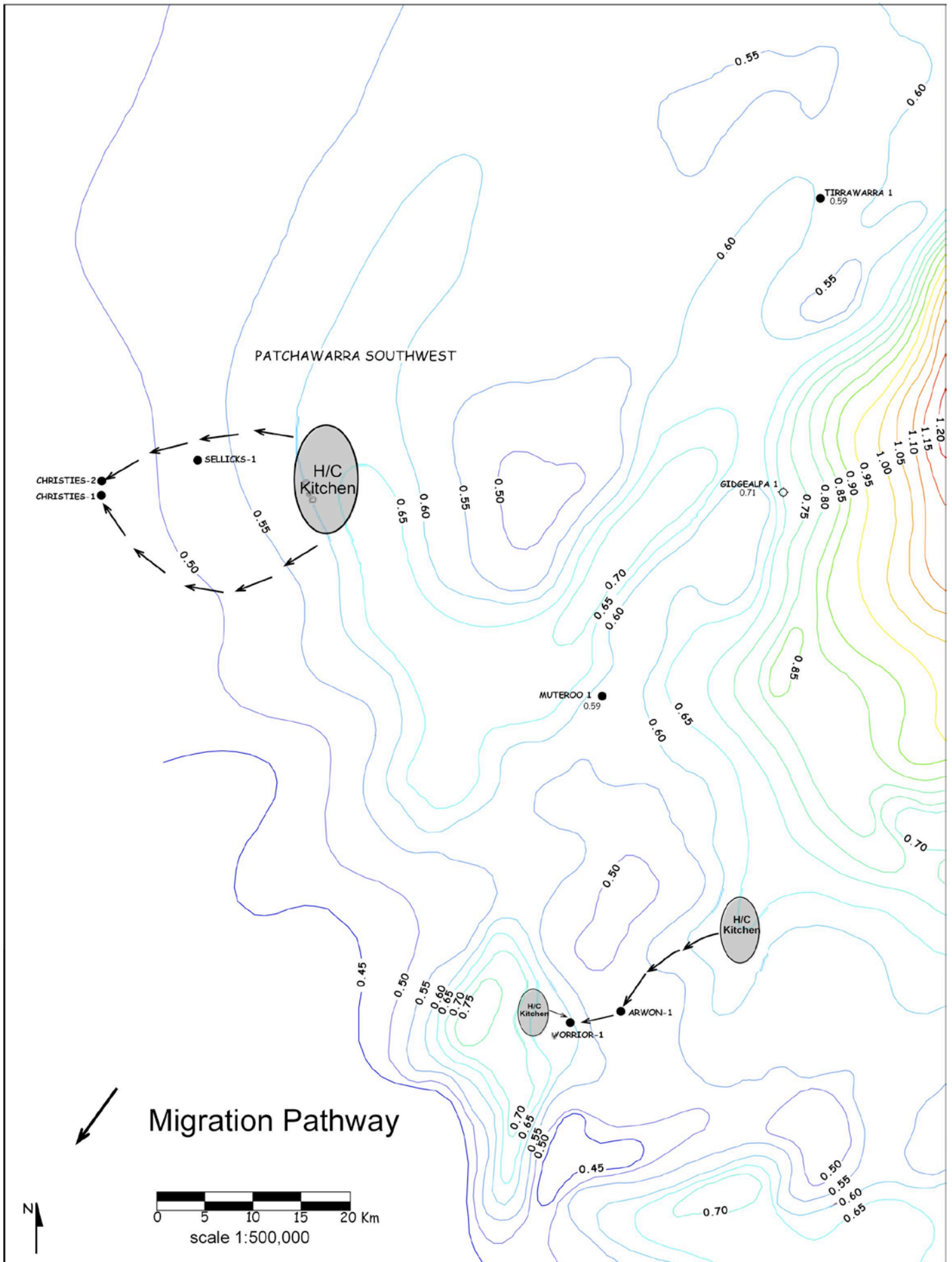


Figure 8b

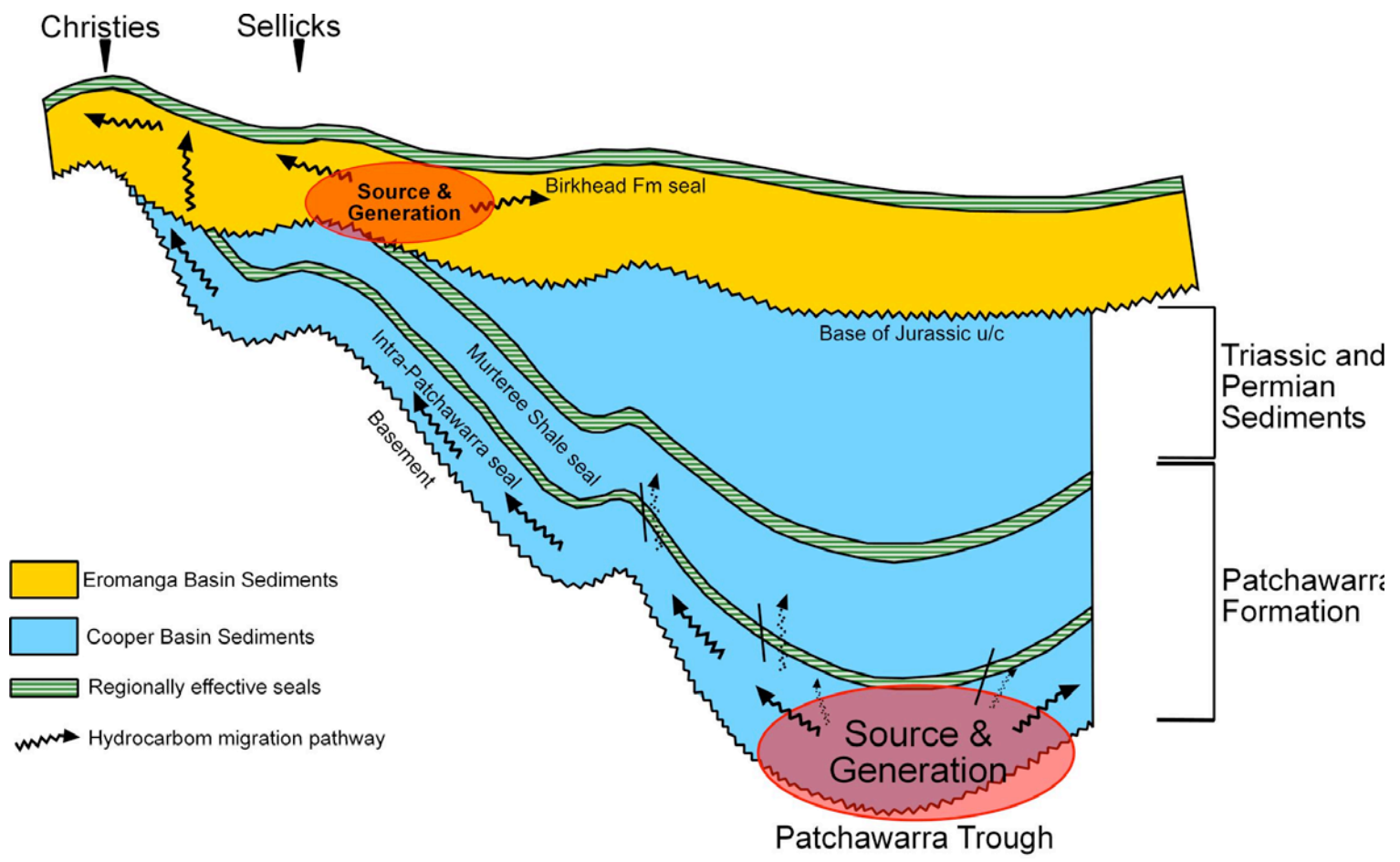
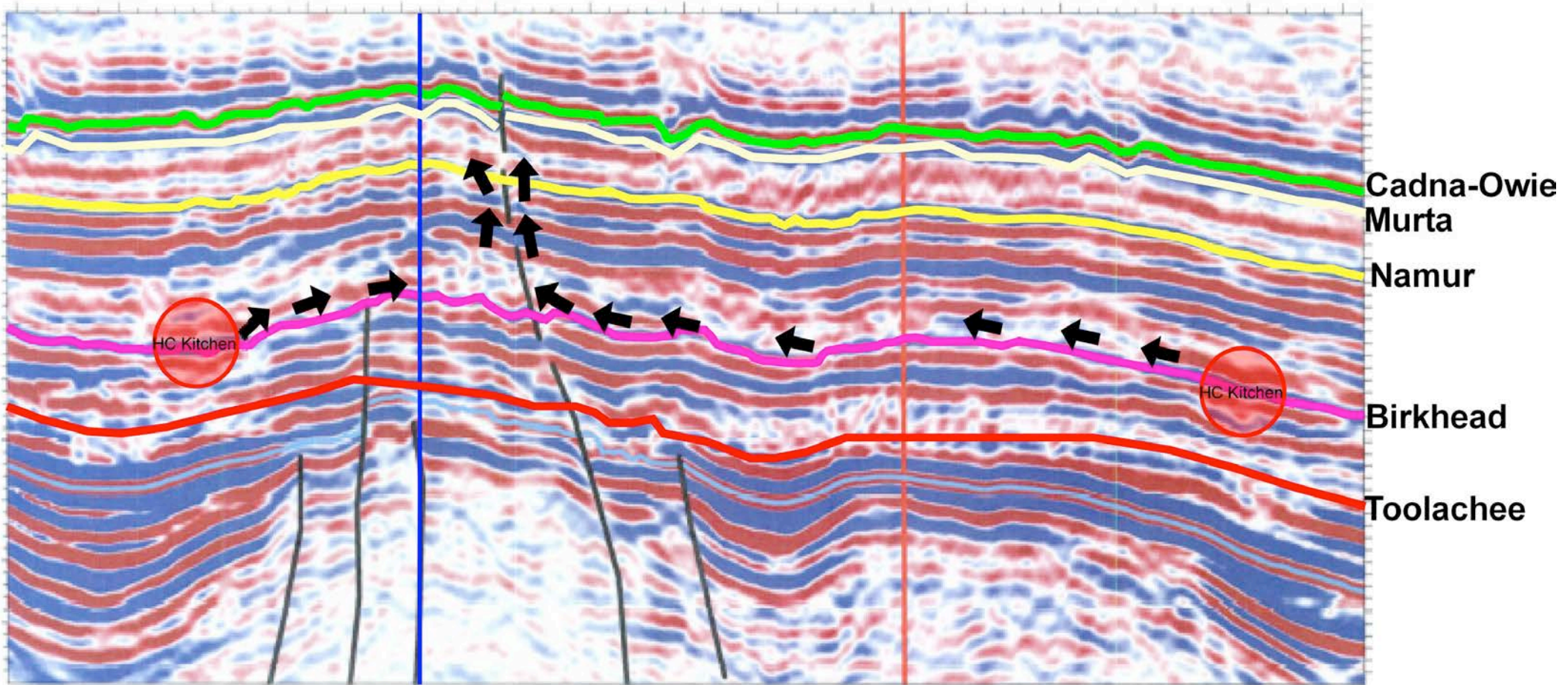


Figure 9

Figure 10

Warrior-1

Arwon-1



Cadna-Owie  
Murta

Namur

Birkhead

Toolachee

HC Kitchen

HC Kitchen

➔ Migration Pathway

**Table 1**

Well	DST*	Depth interval (m)	Location	Formation Name	API Gravity (20°C)	Pour Point (°C)	Sulphur Content (wt%)	Kinematic Viscosity @ 40°C (cSt)	Flow Rate (bopd)
Sellicks-1	1	2058.1 – 2071.7	Lat:27°55'48.47"S	Patchawarra	57.22	N/A	0.04	0.96	1915
	2	2076.5 - 2086	Long:139°28'35.27"E	Patchawarra	54.50	N/A	N/A	N/A	N/A
Christies-1	1	1607.7 – 1622	Lat: 27°58'47.39"S Long: 139°22'22.97"E	Birkhead	45.40	15.00	0.11	2.64	246
Christies-2	1	1344.4 – 1352	Lat: 27°58'53.82"S Long: 139°22'15.83"E	Namur	44.04	21.00	0.03	3.89	1773
Arwon-1	1	1357.8 - 1368	Lat: 28°24'21.16"S Long: 139°50'02.72"E	McKinlay	48.39	3	N/A	2.267	60
Worrior-1	1	1328 – 1335	Lat: 28°25'06.94"S Long: 139°48'42.89"E	McKinlay	48.18	6	N/A	2.54	1600
	2	1553 – 1569		Birkhead	52.19	3	N/A	1.55	200
	3	1579 - 1585		Hutton	52.5	-9	N/A	1.01	2880
	4	1712-1719		Patchawarra	52.2	N/A	N/A	N/A	60

\*Drill Stem Test

**Table 2**

Well	DST	Sample fractions (%)		
		Saturates	Aromatics	Resins and Asphaltenes
Arwon 1	1	68.79	3.40	27.82
Christies 1	1	83.14	7.02	9.83
Christies 2	1	79.13	4.54	16.33
Sellicks 1	1	38.92	4.09	56.99*
	2	59.95	11.85	28.19
Worrior 1	1	71.73	1.84	26.43
	2	56.15	2.62	41.23
	3	40.79	1.83	57.39*
	4	26.05	0.11	73.84*

\* Includes Asphaltenes



**Table 3**

Trough	Well	Formation	Methylphenanthrene distributions				
			MPI-1	MPI-derived Rc (%)	1MP/9MP	2MP/1MP	TNR-1
Patchawarra Trough	Sellicks-1*	Patchawarra	0.802	0.881	0.583	1.172	0.629
		Patchawarra	0.792	0.875	0.637	1.025	0.655
	Christies-1	Birkhead	0.361	0.616	1.651	0.328	0.345
	Christies-2	Namur	0.415	0.649	1.287	0.400	0.443
Wooloo Trough	Arwon-1	McKinlay	0.367	0.620	1.552	0.337	0.438
	Worrior-1	McKinlay	0.385	0.631	1.602	0.354	0.464
		Birkhead	0.452	0.671	1.394	0.472	0.534
		Hutton	0.448	0.669	1.248	0.522	0.565
Family 1 Permian end-member oils	Strezlecki-10	Toolachee	0.71	0.83	0.66	1.15	0.63
	Moorari-1	Tirrawarra	N/A	1.00	0.73	1.45	N/A
Jurassic end-member	Moorari-4	Birkhead	N/A	0.52	7.66	0.11	N/A

\* Family 2 end-member oil

**Table 4**

Trough	Well	Formation	TMN and MP Source Parameters		Retene and DMP source parameters	
			log (1,2,5 -TMN/1,3,6 - TMN)	log (1MP/9MP)	log (1,7- DMP/X)	log (R/9-MP)
Patchawarra Trough	Sellicks 1	Patchawarra	-0.005	-0.234	-0.433	-0.302
		Patchawarra	-0.041	-0.196	-0.406	-0.311
	Christies 1	Birkhead	0.736	0.218	0.063	0.704
	Christies 2	Namur	0.633	0.110	-0.182	0.749
Wooloo Trough	Arwon 1	McKinlay	0.553	0.191	0.088	0.422
	Worrior 1	McKinlay	0.670	0.205	0.095	0.332
		Birkhead	0.450	0.144	0.009	-0.027
		Hutton	0.402	0.096	-0.045	-0.290
Family 1 Permian end-member oils	Strezlecki-10	Toolachee	-0.310	-0.180	-0.523	-2
	Moorari-1	Tirrawarra	-0.949	-0.139	-0.427	-1.505
Jurassic end- member	Moorari-4	Birkhead	1.132	0.884	0.669	0.903

TMN = trimethylnaphthylene, MP = methylphenanthrene, DMP = dimethylphenanthrene, R = retene, X = 1,3- 2,4- 3,9- 2,10- 3,10- DMP