THE OILS OF WESTERN AUSTRALIA

PETROLEUM GEOCHEMISTRY AND CORRELATION

WITH CONTRIBUTIONS FROM:

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CHAPTER I
OVERVIEW OF STUDY

Petroleum Supersystems and Oil Families

A petroleum systems approach to understanding and predicting hydrocarbon occurrences in Australia was developed as a result of regional and continent wide studies by AGSO's *Australian Petroleum Systems Project (APS)* team and its industrial sponsors (Bradshaw, 1993; Bradshaw *et al*., 1994), managed through the Australian Petroleum Industry Research Association (APIRA). While the *Oils of Australia Project* developed as a separate exercise, there are many interconnecting and mutually beneficial observations and concepts that enhance both of these efforts. Consequently, this report seeks to integrate the information obtained from a purely chemical analysis of a large suite of west Australian oils and condensates, with some of the broad, general lessons of the twelve years of the *APS and other APIRA projects*. We also rely heavily on geological knowledge, ideas and concepts developed by AGSO's Marine, Petroleum and Sedimentary Resources Program team and, most importantly, the published information and experience of individuals and company teams of the Australian petroleum industry.

Comparable tectonic regimes and paleogeographic settings create the principal controls on source rock facies and organic matter type which are the first links for establishing a broad category of a petroleum 'supersystem'. Five of the seven petroleum supersystems recognised in Australia's Phanerozoic Basins (**Table I-1**) are represented in the western half of the continent (here meaning Western Australia, the Northern Territory and corresponding offshore continental margins; **Figure I-1**). The earliest of these, the Larapintine Supersystem (Bradshaw, 1993; Bradshaw *et al*., 1994), is best represented in the onshore Canning and Arafura Basins. In an analogy to the distribution of sediments of the Early Ordovician 'Larapintine Seaway' (Nicoll *et al*., 1988), it takes its name from the sinuous shape of Larapinta, the Dreamtime Snake. Lower Paleozoic marine facies including carbonates, clastics and evaporites, were deposited during a tropical regime which fell between the major glacial epochs of the latest Precambrian and the Permo-Carboniferous and comprise a family of source rocks, reservoirs and seals.

An Australia-wide and prolonged period of episodic tectonism, the Alice Springs Orogeny, occurred during the Devonian to Carboniferous, and brought to a close the Larapintine regime. It has been postulated (Veevers, 1984) that this peak in the orogeny produced the elevation that triggered ice accumulation on the southern continents and heralded the beginnings of the glacial Gondwanan Supersystem.

Significant climate change and 20 degree shift south in latitude for the supercontinental landmass mark a transitional period of sedimentation during the Carboniferous that separates the Larapintine Supersystem from the Gondwanan Supersystem. Early and Late Carboniferous regional unconformities bracket this 'Transitional system', also known as Larapintine 4 (Kennard *et al*., 1994). This Larapintine/Gondwanan Transitional system is mainly recognised in the Canning and

Table I-1. Summary of Australian Petroleum Systems.

PETROLEUM SUPERSYSTEM	AGE	PALEOGEOGRAPHIC & TECTONIC SETTING	SUBSYSTEMS & SOURCE UNITS
Larapintine	Cambrian to E. Carboniferous	Paleotropics; warm, often shallow epicontinental seaways; Alice Springs Orogeny compressive regime.	**L1.** Basinal shales & carbonates - Elcho Is. Fm. **L2.** Shallow marine carbonates & shales - Goldwyer, Nita & Bongabinni Fms. **L3.** Basinal shales & carbonates - Gogo, Luluigi, Clanmyer & Laurel Fms.
L/G Transitional	Middle to Late Carboniferous	Cooling with shift to high southerly latitudes; climax of Alice Springs Orogeny	**L/G.** Marine clastics - Bonaparte, Milligans & Anderson Fms.
Gondwanan	Late Carboniferous to Permian	Pervasive glacial influence; high paleolatitudes; major extensional regime.	**G1.** Terrestrial, carbonaceous shales & coals- Irwin R. & Sue CM, Carynginia Fm **G2.** Transgressive calcareous shales - Kockatea & Locker Sh.
Westralian	Mesozoic	Temperate to tropical; western margin transition from Tethys to Indian Ocean; L. Triassic compression, minor extension, subsidence & formation of major depocentres.	**W1.** Paralic shales & coals - Mungaroo Fm. **W2.** Marine shales & terrig. OM deposited in restricted depocentres-Dingo, Legendre Fms. & Flamingo Group.
Austral	Jurassic to Cainozoic	Temperate; southern margin Australia-Antarctica rift; southern Indian Ocean & Tasman Sea extension, subsidence & Miocene compression.	**A1**. Fluvio-deltaic sources in Jurassic - Cattamarra CM. **A2**. Lacustrine shales in Jurassic & Cretaceous - Athol, Parmelia, Yarragadee Fms.
Capricorn	Cainozoic	Subtropical to tropical; extension & subsidence	No identified sources in WA/NT
Murta	Mesozoic	Temperate; interior basins sag; Late Cainozoic compression	No identified sources in WA/NT

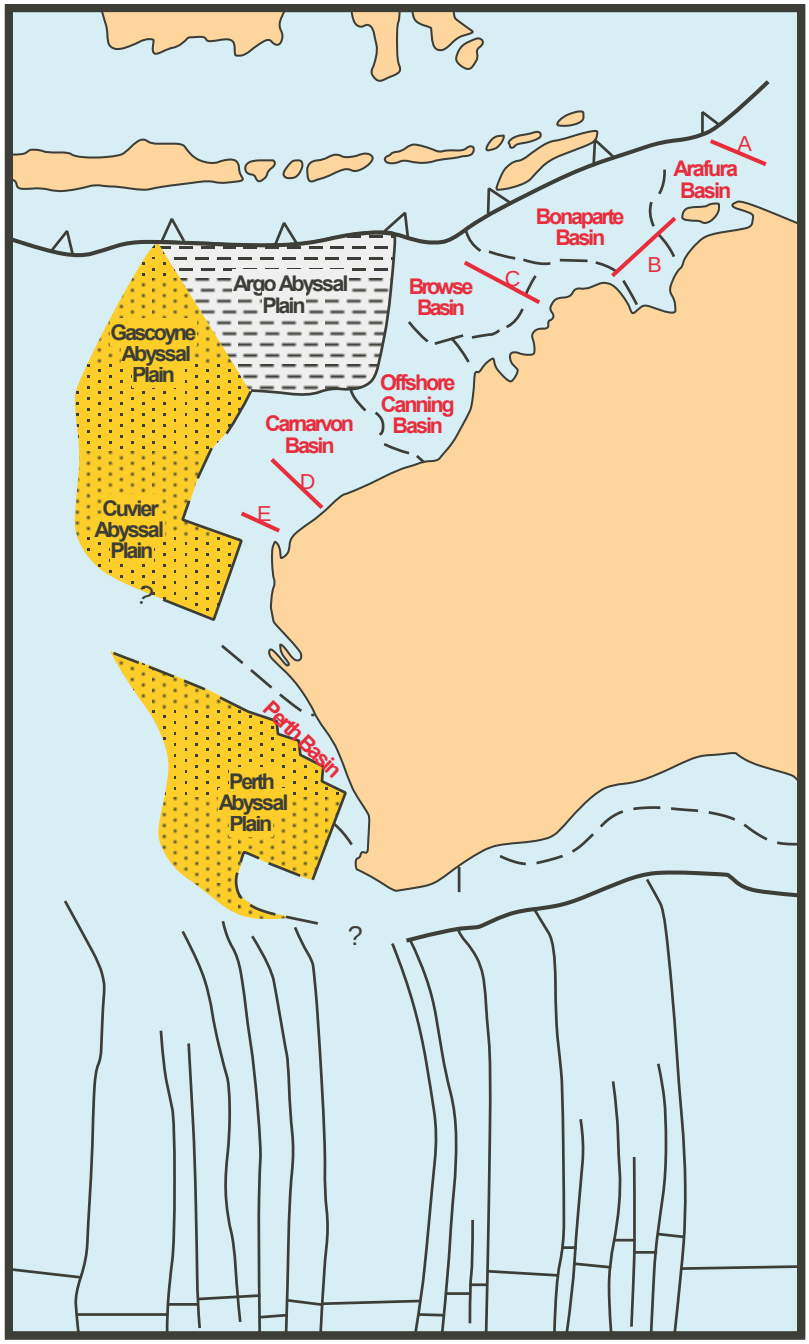


Figure I-1. Principal Tectonic Elements and Basins of the West Australian Margin. Unpatterned parts of the offshore area represent the continental margin with the principal basins marked. Patterned areas are floored by oceanic crust, with the different patterns representing different episodes of seafloor spreading. The locations of some key deep seismic profiles are shown by solid lines; A - AGSO line 118/15, B - AGSO line 100/003, C - AGSO line 98/002, D - GSI line 86/3185, E - AGSO line 110/11. (After Etheridge & O'Brien, 1994; Fig.1).

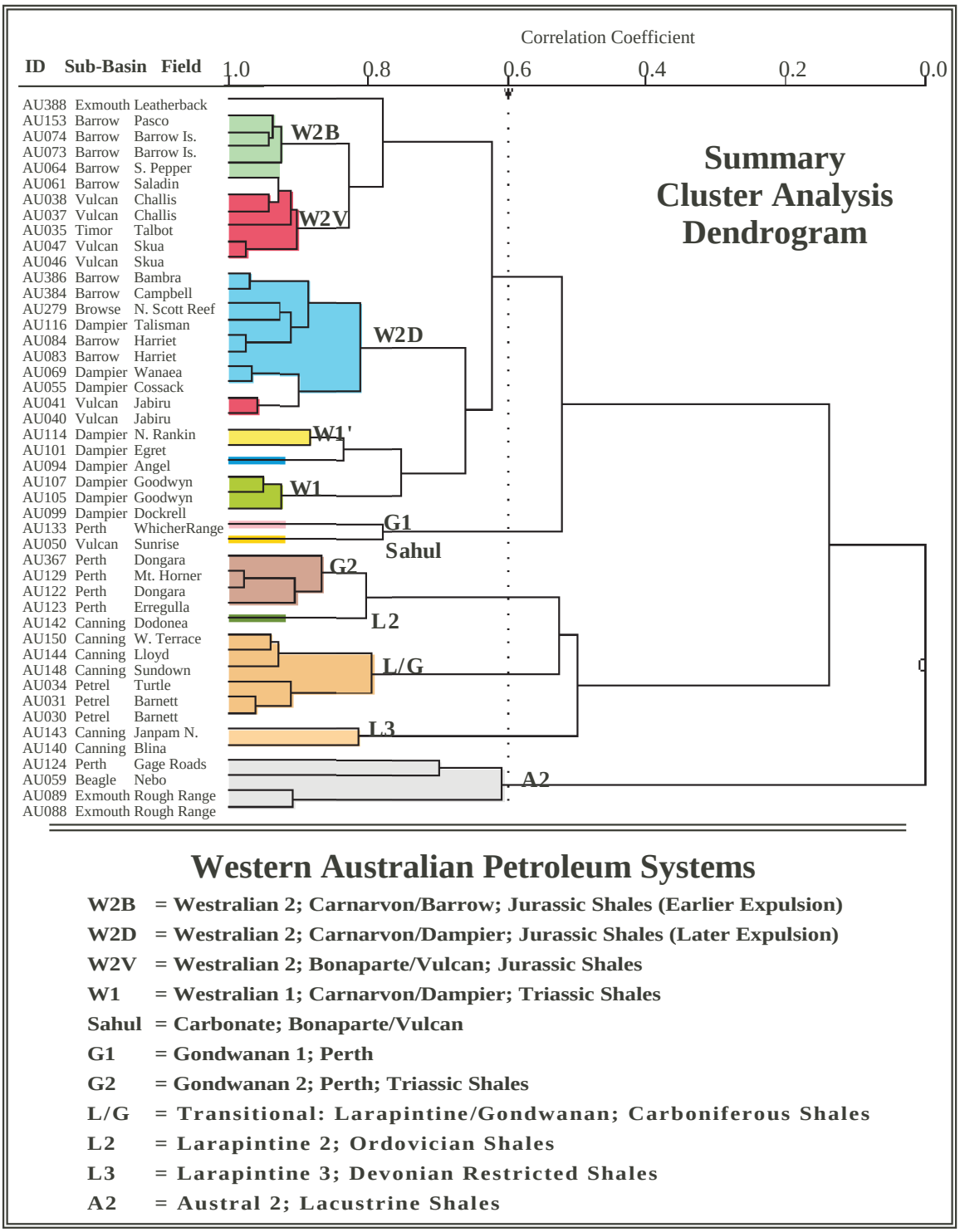
Bonaparte Basins and is characterised by thick syn-tectonic sedimentation in restricted areas - respectively, the Fitzroy Trough- Gregory Sub-basin and the Petrel Sub-basin.

The economically significant petroleum deposits of west Australia (WA and NT) have been classified within the Gondwanan and Westralian Supersystems (Bradshaw *et al*., 1994) and are represented in all offshore basins of the North West Shelf. The Gondwanan Supersystem recognises the polar position of the then supercontinent and the shared periglacial environments recorded in rift basins of the western margin, in pericratonic basins across central Australia and in foreland basins to the east of the continent. The Gondwanan Supersystem is the predominant habitat for economic petroleum in the Perth Basin in southern WA, and is characterised by glacigene sediments in all basins with the probable exception of the Arafura Basin in the extreme north. Early Triassic marine shales and sandstones with a predominant terrestrial component are the most important source, reservoir and regional seal facies of the Gondwanan System in WA. However, there also are some fully terrestrial sources in the Irwin River and Sue Coal Measures of the Perth Basin which share the characteristics of the Permian sources for eastern Australia's Gondwanan petroleum provinces.

The bulk of economic WA and NT oil, condensate and gas occurs within the Westralian Supersystem, sourced from either predominantly terrestrial source rocks of Middle to Late Triassic age (Westralian 1) and/or predominantly marine source rocks of Late Jurassic age (Westralian 2). As discussed later, basin architecture, styles of sedimentation and the course of maturation, migration, entrapment and, finally, leakage were all fundamentally determined by events of Gondwanan age.

A fifth petroleum supersystem, termed the Austral Supersystem, has been used to systematise the Cretaceous to Cainozoic of Australia's southern margin and is characterised by terrestrial sedimentation in rift settings. Marginally economic Jurassic gas and condensate and non-economic Cretaceous oil in the Perth Basin have been assigned to this supersystem because of similarities of habitat to those of the Gippsland and Otway Basins.

These five petroleum supersystems originally established on geological criteria are directly mirrored in the geochemistry of the oils as shown in **Figure I-2**. This hierarchical dendrogram from cluster analysis was constructed using carbon isotope and terpane/sterane biomarker data from a representative set of oils, allowing end member families to be easily recognised. This analysis is a strong validation of the petroleum systems concept, although it is not unexpected since oil compositions reflect source rock character as determined by geological factors such as depositional environment and tectonic setting. However, new relationships were revealed in the dendrograms and related principal component analyses that were not apparent in the geological analysis.



Western Australian Petroleum Systems

W2B = Westralian 2; Carnarvon/Barrow; Jurassic Shales (Earlier Expulsion)
W2D = Westralian 2; Carnarvon/Dampier; Jurassic Shales (Later Expulsion)
W2V = Westralian 2; Bonaparte/Vulcan; Jurassic Shales
W1 = Westralian 1; Carnarvon/Dampier; Triassic Shales
Sahul = Carbonate; Bonaparte/Vulcan
G1 = Gondwanan 1; Perth
G2 = Gondwanan 2; Perth; Triassic Shales
L/G = Transitional: Larapintine/Gondwanan; Carboniferous Shales
L2 = Larapintine 2; Ordovician Shales
L3 = Larapintine 3; Devonian Restricted Shales
A2 = Austral 2; Lacustrine Shales

Figure I-2. Cluster Analysis Dendrogram obtained using biomarker and carbon isotope data for a representative set of WA oils showing strong family correlations reflecting petroleum supersystem relationships.

These include:

- Geologically-based predictions of Petroleum Systems (Bradshaw *et al*., 1994) are generally confirmed by the geochemical grouping of oil families, e.g., Family L/G (Transitional Larapintine/Gondwanan) oils from both Bonaparte and Canning Basins have a high degree of chemical affinity as shown in the cluster analysis.

- Westralian 2 oil families are generally similar across the North West Shelf as can be seen in the composite North West Shelf dendrogram (**Figure I-2**). Jurassic-sourced Vulcan (Jabiru) and Dampier oils can overlap. This is probably because their similarly high degree of thermal maturity results in a close alignment (overall) of their geochemical parameters.

- Rankin Trend condensates invariably have high contents of demethylated hopanes combined with a normal alkane signature indicating a component of paleo-biodegraded oil mixed with freshly generated hydrocarbons. The source of the biodegraded component is not known but could possibly be from an older (i.e. Paleozoic) source.

- The North Scott Reef-1 oil from the Browse Basin shows geochemical affinity with Dampier oils (Family W2D) suggesting a Late Jurassic source kitchen, with geochemical character akin to the Lewis Trough, exits in the vicinity.

- A wide spectrum of thermal maturity is evident in Family W2V oils (Talbot < Skua < Challis < Jabiru) which may be significant in reconstructing their migration histories.

- Oil maturity trends within the Carnarvon Basin oil families are also observed with possible migration direction implications.

- Some vagrant condensates in the Carnarvon Basin have distinctly heavy carbon isotopic signatures in both saturates and aromatics (e.g. West Tryal Rocks-2, -3 and Barrow Deep-1). This is reminiscent of the signature for Permian oils seen Australia-wide and also noted in the Petrel-4 condensate in the Petrel Sub-basin where a Permian source is inferred on geological grounds. It is therefore possible that the West Tryal Rocks and Barrow Deep-1 liquids have a Permian source or a component of Permian organic matter in their makeup. An alternative explanation is that they are very late stage products from the Dingo Claystone, generated at a quite different time to the bulk of the hydrocarbons from this unit.

- Puffin oils of Family W2V (predominantly Jurassic source) in the Vulcan Sub-basin are isotopically heavier than the other oils in this family and, hence, appear to contain an additional component of Permian-sourced light oil.

- Paleobiodegradation is a feature of Petrel Sub-basin and Carnarvon Basin condensates/light oils indicating long periods of reservoir charging and burial.

- Sundown oils of Canning Basin Family L/G appear to contain an additional component of isotopically light Ordovician oil.

- A geographically widespread family of terrestrially-derived Austral oils (Nebo-1, Rough Range-1 and Gage Roads-1) has been identified. These oils originate from pods of predominantly non-marine source rocks deposited in lakes of the incipient rift preceding the break-up with Greater India.

- A distinct chemical difference in Late Jurassic (Westralian 2) oils from the Carnarvon Basin where Dampier Family (W2D) oils can be discerned from Barrow Family (W2B) oils on the basis of their biomarker distributions and isotope composition.

- Oils of the Harriet, Bambra, Campbell, Tanami and Rosette accumulations have a strong chemical affinity with those of the Dampier Sub-basin suggesting a nearby depocentre of 'Dampier' source rock may exist south of the main Lewis Trough. Long distance migration pathway south from the Lewis Trough is an alternative that could be tested geologically.

- A distinct group of Bonaparte Basin (Sahul Platform) oils with a calcareous element in their source rock lithology (Sunrise-1 and Troubadour-1).

As will be discussed later, the biomarker distributions and their statistical analysis disclose complex and subtle variations in the Westralian oils and condensates of the Carnarvon Basin (see later **Figure III-21**; Carnarvon Basin dendrogram) that appear to reflect two and possibly three major source rock units in addition to the effects of differing maturation regimes, migration and mixing histories. The results also reveal the unexpected occurrence of Austral (lacustrine) oils in this basin.

Finally, a series of North West Shelf maps showing the geographical relationships among the various oil families within the different basins are shown in **Figures I-3**, **I-4**, **I-5, I-6** and **I-7** for the Bonaparte, Carnarvon (Dampier and Barrow), Canning, and Perth Basins, respectively.

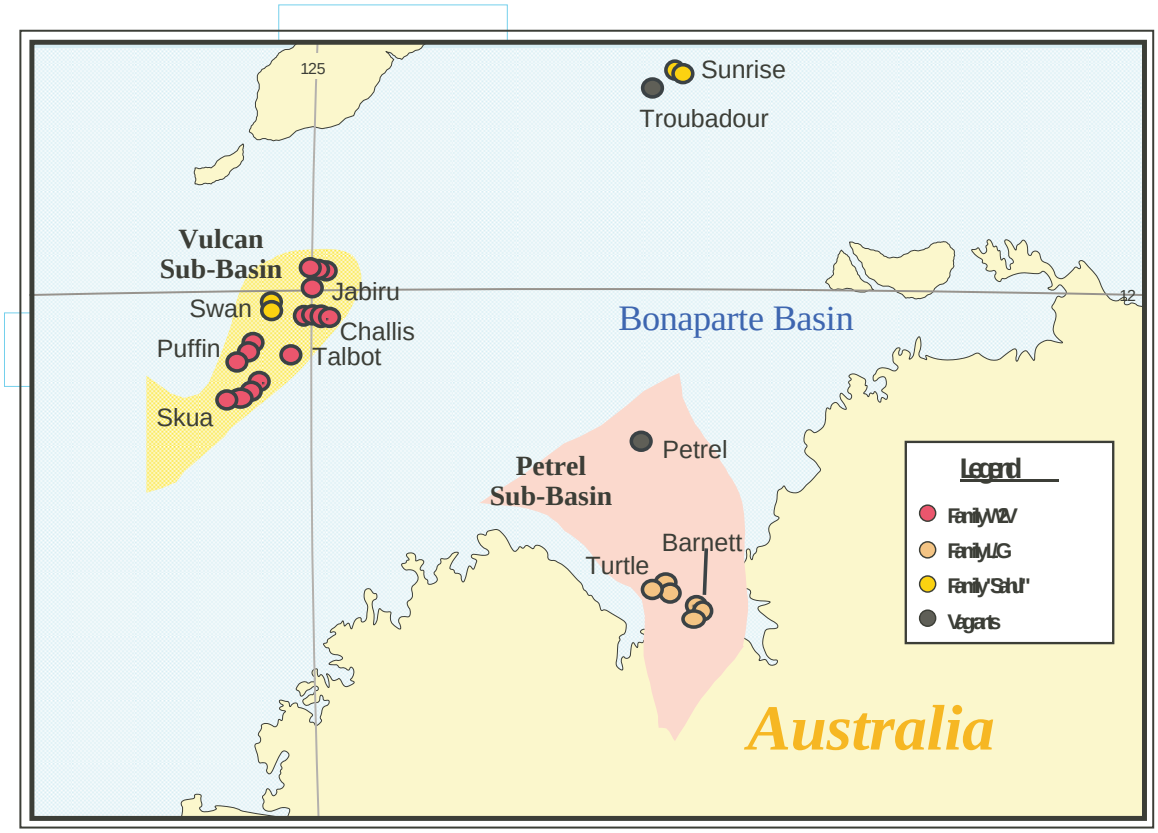


Figure I-3. Geographic Distribution of Bonaparte Basin Oil Families
(see **Figure III-14** Dendrogram, p. III-32).

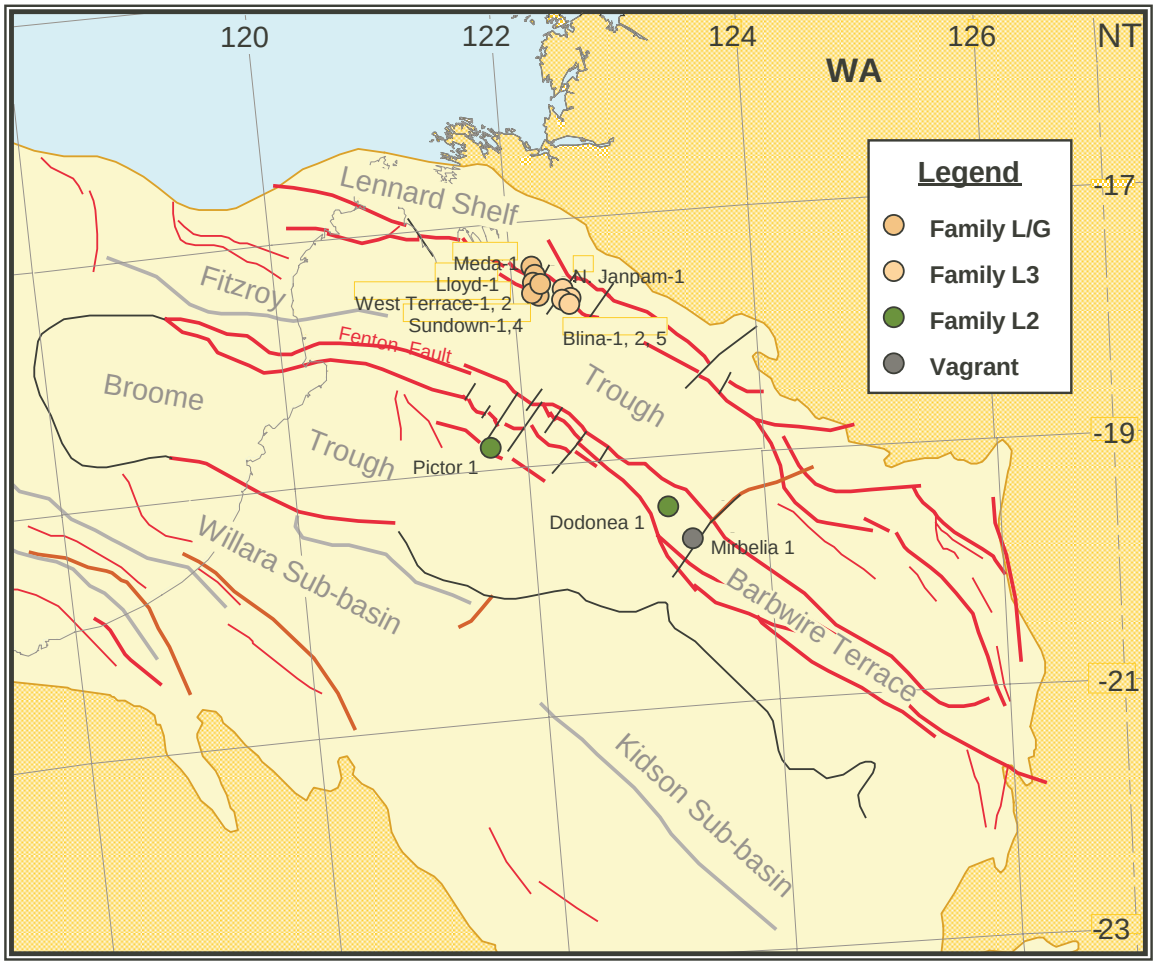


Figure I-4. Geographic Distribution of Canning Basin Oil Families (see **Figure III-18** Dendrogram, p. III-40).

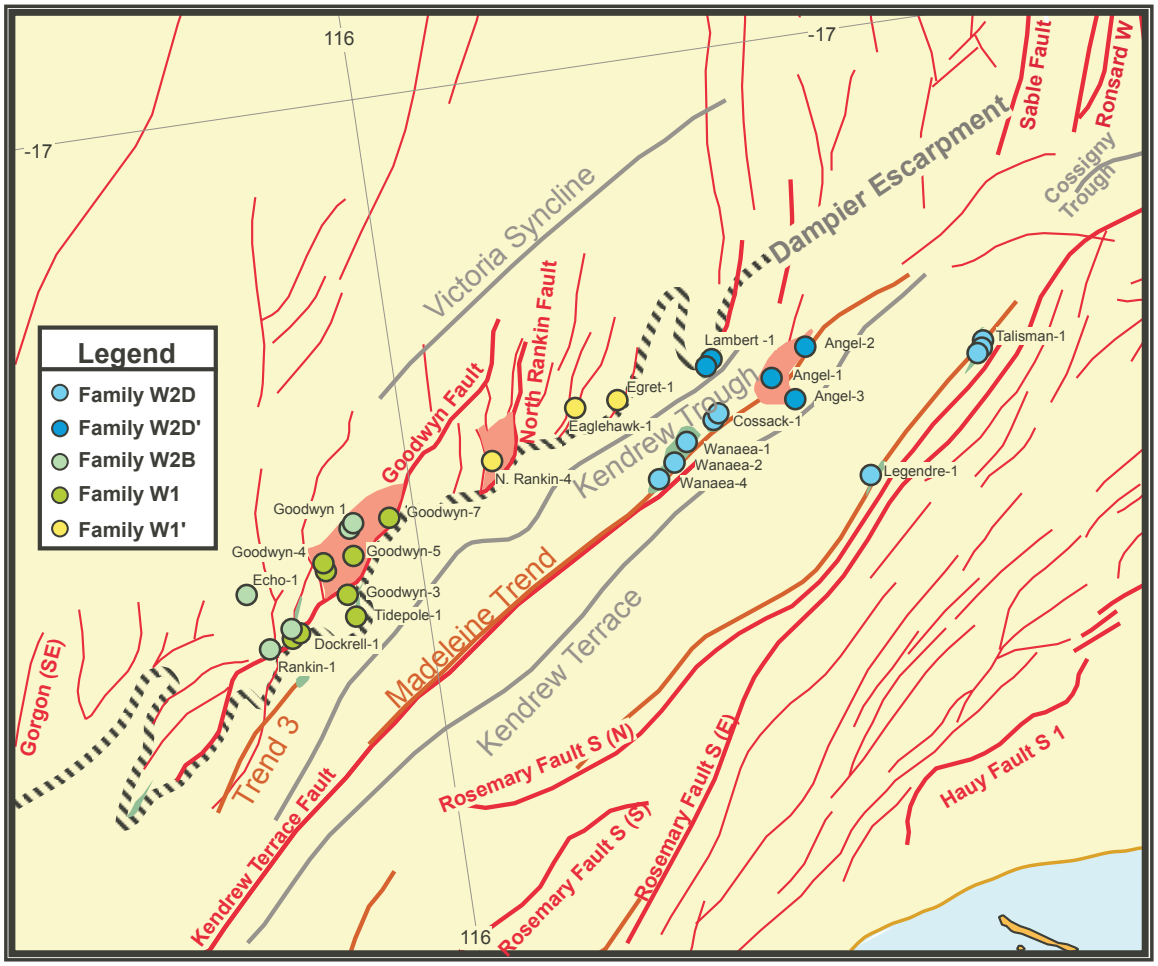


Figure I-5. Geographic Distribution of Dampier Sub-Basin (Carnarvon Basin) Oil Families (see **Figure III-21** Dendrogram, p. III-45).

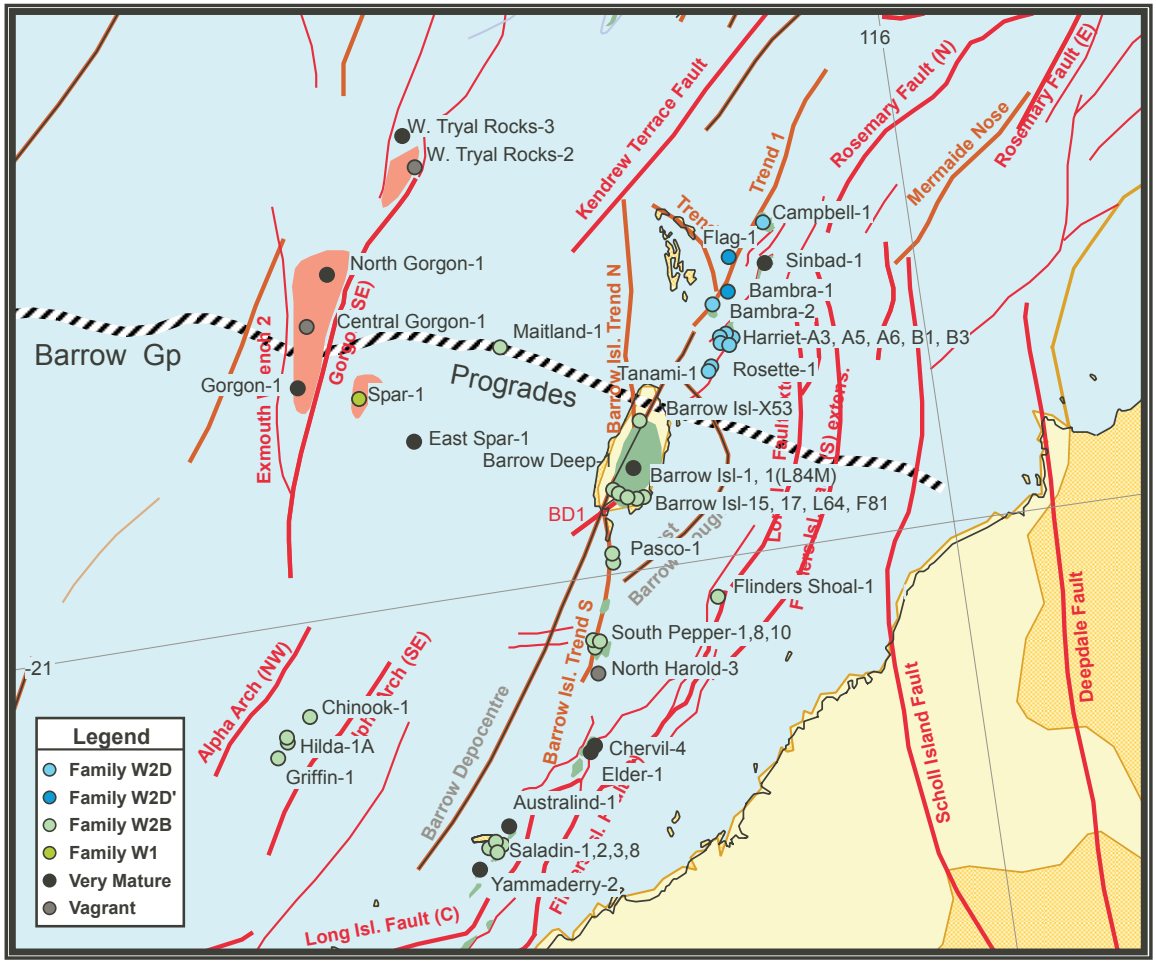


Figure I-6. Geographic Distribution of Barrow Sub-Basin (Carnarvon Basin) Oil Families (see **Figure III-21** Dendrogram, p. III-45).

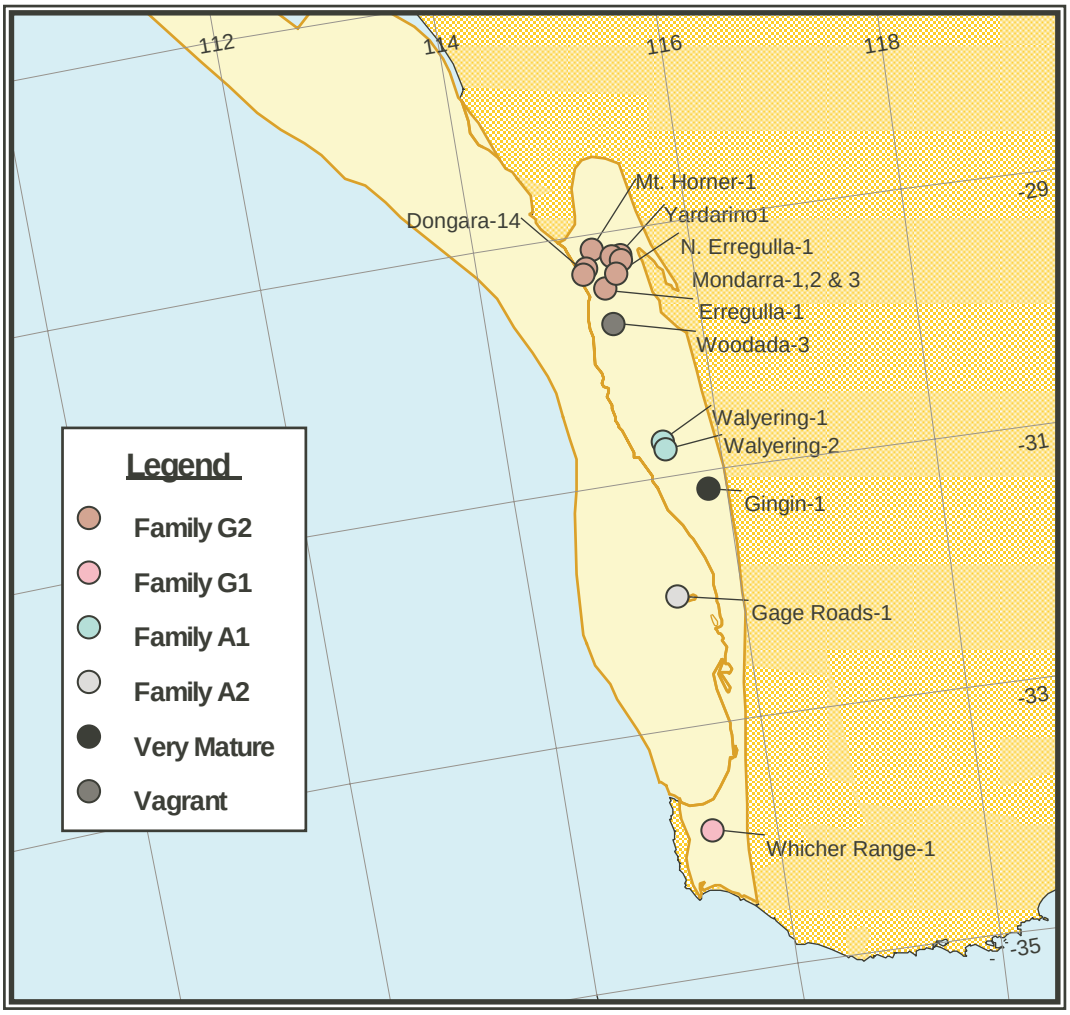


Figure I-7. Geographic Distribution of Perth Basin Oil Families
(see **Figure III-25** Dendrogram, p. III-53).

CHAPTER II
THE GEOLOGICAL SETTING OF WESTERN AUSTRALIAN PETROLEUM DEPOSITS

Tectonic Setting

This chapter outlines the regional tectonic and geological setting and basinal stratigraphy for the economic and sub-economic petroleum accumulations discovered to date in Western Australia and the Northern Territory. Since petroleum systems are intimately related to their tectonic setting, a brief synopsis of the various hypotheses for the formation and age of the Western Australia offshore basins are also given here.

In the earlier stages of exploration, the Western Australia margin was believed to be a passive continental margin with its structure dominated by normal faults and overall subsidence associated with the decay following the onset of seafloor spreading. In line with this theory, the Western Australia offshore basins were considered to have formed as a result of one or more periods of Mesozoic rifting (extension) followed by broad scale subsidence or sag (e.g., Barber, 1988; MacDaniel, 1988; Parry and Smith, 1988; Woodside Offshore Petroleum Exploration Pty. Ltd., 1988; Pattillo and Nicholls, 1990; Woods, 1992). This 'rift-sag' or 'rift-drift' tectonic setting for the Western Australia margin is extensively documented and greatly influenced the early exploration strategies in the region. The 'rift-sag' phase of basin development is attributed to the onset of seafloor spreading during the late Middle Jurassic (late Callovian) in the Argo Abysal Plain, and the Early Cretaceous (Valanginian) in the Cuvier-Gascoyne Abyssal Plains.

In fact, the Western Australia margin has been formed by a multitude of tectonic events which continue from the extensional episodes in the Archaean and Proterozoic through to continental convergence in the Miocene-Pliocene. These individual events, as well as interactions between these events and the accompanying paleogeographic regimes, have all contributed, to varying extents, to the development of the petroleum systems that presently exist along the margin (e.g. Yeates *et al*., 1987; Bradshaw *et al*., 1988; Veevers *et al*., 1991; O'Brien *et al*., 1993).

The earliest well documented tectonic event dates from the Proterozoic (approximately 1800 Ma BP), when crustal extension led to the development of the Kimberley Basin and Capricorn Orogen (Etheridge and Wall, 1994). These basins developed as a result of approximately north-east extension and extended out under much of the present day North-West Shelf. Rift faults trended at approximately 300-310°, a structural grain which still dominates the regional gravity, magnetics and geology of northern Australia. A conjugate set of fractures/structures trended approximately north-east, almost orthogonal to the rift fault orientation. Older, probably Archaean, north-south-trending fractures are also evident of the Kimberley and Pilbara Blocks. These fundamental crustal lineaments have been progressively reactivated by subsequent tectonic events since the Proterozoic, and have acted as long-lived zones of weakness which localised structuring.

In the Early Ordovician, regional lithospheric thinning, probably on an almost north-south to north-northeast azimuth, resulted in the development of broad, intra-cratonic sag basins. These sags are best documented in the onshore Canning Basin, but also certainly developed within the Petrel Sub-basin. Their presence under parts of the Carnarvon Basin and Arafura Sea is more problematical. In the Canning Basin, progressive marine inundation peaked with the deposition of the Goldwyer Formation, a sub-tidal sequence of shales and limestones which is rich in the oil-prone alga *G. prisca,* a globally prevalent fossil at this time. Marine regression terminated deposition of the Goldwyer Formation, and resulted in the progradation of the inter-tidal to supra-tidal Nita Formation, a reservoir unit. Continued regression resulted in widespread continental environments being established, with deposition of the sealing facies of the Carribuddy Formation.

Basin desiccation in the Late Ordovician-Silurian resulted in widespread evaporite sedimentation, with extensive salt deposition in the Kidson and perhaps Worral Sub-basins of the Canning Basin. Salt was also deposited over at least parts of the Petrel rift system and wider Timor Sea, which at this time was probably a series of 80-100 km wide, intra-cratonic rift segments (O'Brien *et al*., 1993). This salt has formed the piercement structures which are now observed in the Sandpiper-1 well in the Petrel Sub-basin, and the Paqualin-1 well in the Vulcan Sub-basin.

Progressive episodes of shallow marine incursions and basin desiccation continued throughout the Silurian and Middle Devonian. In the late Middle Devonian (Givetian), a major extensional episode, which is evident in both the Canning Basin and the Petrel Sub-basin, began. This extensional event continued until the Early Carboniferous (Tournasian). The extensional azimuth was approximately north-east, which resulted in the formation of north-west trending rift faults. As with the Early Ordovician structuring, this event was dominated by lithospheric (lower crustal and upper mantle), rather than upper crustal, extension.

The pre-existing basement fabric, particularly the north-east trending Proterozoic grain, strongly controlled the development of the upper crustal rift segments (O'Brien *et al*., 1996). In the northern Petrel Sub-basin, for example, the polarity of the rift flipped across a major fracture system, whereas in the southern Joseph Bonaparte Gulf, the Cambridge Trough and Lacrosse Terrace were terminated by another fracture. These fractures behaved basically as heterogeneities which acted to relay and/or flip the polarity of the developing extensional faults, and resulted in the development of highly compartmentalised (segmented) rift systems.

Following the cessation of rifting, the inboard parts of the Petrel and Canning rift systems thermally subsided, with the attendant deposition of 15-20 kms of largely unstructured Permo-Triassic post rift sediments. In contrast, outboard of these intra-cratonic rifts, the Western Australia margin 'proper' was soon subjected to a major extensional event. This event initiated the development of the Westralian Superbasin, and was a key tectonic event in establishing the present day architecture of almost the

entire Western Australia margin. It is likely that the rifting began in the mid-Carboniferous (Visean), for this correlates with a major unconformity represented in the Carnarvon (Bentley, 1988) and Arafura Basins and the Petrel Sub-basin (Bradshaw *et al*., 1992). Furthermore, fission track data from the Amadeus, McArthur, Canning, Arafura and Pilbara Basins (Bradshaw and Vizy, 1990) show that this unconformity corresponds to a major thermal event which significantly affected the maturation of Paleozoic source rock units. The proposed incept age for rifting correlates with the peak of the Alice Springs Orogeny.

This extension event continued until the Early Permian, and was characterised by massive, approximately north-west extension which dramatically thinned the crust from the Carnarvon Basin to the Timor Sea. Whilst most of the thinning was concentrated under what is now the outer shelf and continental slope, localised north-east-trending grabens developed over thinned regions on the inboard parts of the margin. These areas ultimately became features such as the Lewis Trough in the Carnarvon Basin, and the Skua and Cartier Troughs in the Timor Sea. Since these grabens were fault-bounded, and localised by underlying, highly thinned ('necked') and weakened crust they were ideally situated to be strongly reactivated. As with the earlier rift events, the position and orientation of the pre-existing structures strongly influenced the style of structures which developed during this event.

Following cessation of this extensional phase, approximately 10-15 kms of flat-lying, largely unstructured, Permo-Triassic sag phase sediments were deposited over the entire Westralian basin system.

This quiet interval was interrupted in the middle Late Triassic by the most important (from a petroleum standpoint) tectonic event that affected the Westralian Superbasin. This event, which was first documented in the Canning Sub-basin, has been termed the Fitzroy Movement. Its effects are consistent with approximately north-south to north-northwest compression. Whilst the total shortening along the margin is small (<2%), the effects of this event are dramatic. This event produced prominent wrench-related anticlines in the Fitzroy Trough in the onshore Canning Basin, strong reactivation over the large displacement margins in the Petrel Sub-basin, and approximately 4 kms of uplift and erosion in the Arafura Sea. Strongly 'necked' and weakened areas of the crust, such as the proto-Lewis Trough in the Carnarvon Basin (**Figure II-1**), and the proto-Skua and proto-Cartier Troughs in the Timor Sea, buckled and formed broad, crustal scale synclines which localised subsequent Jurassic source rock deposition. Intervening regions formed crustal scale anticlines which were subsequently strongly eroded (e.g. Rankin Trend, Madeleine Trend and Londonderry High).

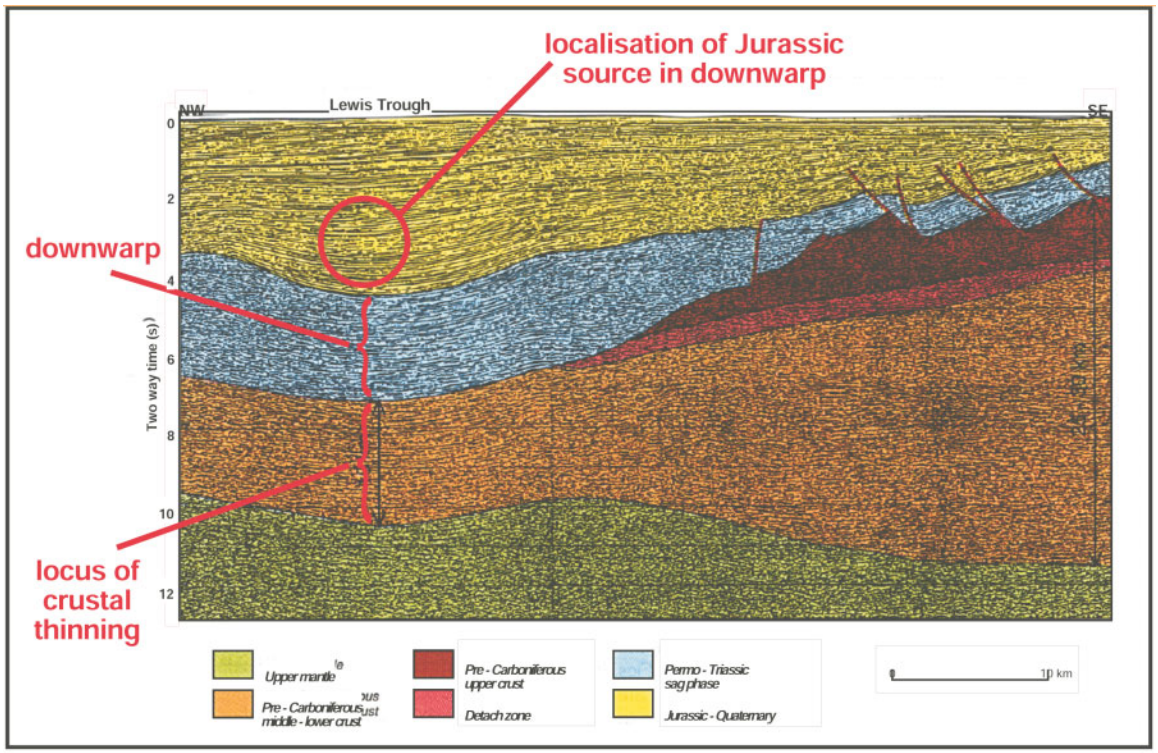


Figure II-1. Part of deep Seismic Profile GSI 86/3185 across the southern part of the North West shelf (see figure I-1, Line D, for location). The interpretation is intended to illustrate the extreme crustal thinning beneath the Dampier Sub-basin, and to demonstrate the relationship between the thinning and Permian extensional structures in the proximal part of the shelf. Where the crust thins or "necks" to about 10 km, the associated downwarp leads to localisation and thickening of Late Jurassic source sediments in the Lewis Trough (after Etheridgeand O'Brian, 1994.)

On a crustal scale, the effects of the Middle and Late Jurassic rifting events, which ultimately led to continental break-up and seafloor spreading, were relatively minor compared to these earlier rift and reactivation events. These events were, however, important in localising source rock deposition.

On the northern and western Australia margins, such as the region through the Timor Sea and Browse Basin, continental break-up occurred in the late Callovian to early Oxfordian, at approximately 155 Ma BP, with the rifting away of Argoland and the formation of the Argo Abyssal Plain. Prior to break-up, the rifting had had little effect through the Vulcan Sub-basin, Malita Graben and Browse Basin. This was because of their inboard location, some 300 kms from the rift axis (which was positioned outboard of the Ashmore Platform). Sedimentation in the Early to Middle Jurassic was dominated by the localised sedimentation of the fluvio-deltaics of the Plover Formation, a high quality reservoir unit with some source potential. However, immediately prior to continental break-up, a low strain (<10%) extensional event took place in the Vulcan Sub-basin, and, perhaps, the Malita Graben. This event resulted in the formation of rapidly subsiding grabens (e.g. the Swan and Paqualin Grabens), which were then inundated by the marine transgression that followed break-up. This confluence of events produced localised, deep water, restricted marine depocentres in which the source rocks of the Late Jurassic (Oxfordian) Lower Vulcan Formation accumulated adjacent to emergent horst blocks, such as Skua, Challis and Jabiru.

Further south, in the Carnarvon Basin, deposition of the source-rich Dingo Formation began at the same time, and in response to the same transgression.

Final continental separation took place later along the southern North-West Shelf than in the Timor Sea. Rifting between Australia and Greater India continued until the Valanginian (~132 Ma BP), when seafloor spreading began and the Cuvier and Gascoyne Abyssal Plains developed.

Post-Valanginian sedimentation in both the Timor Sea and southern North-West Shelf was characterised by increasingly marine influences, with generally minor structural reactivation. In the latest Miocene, however, the effects of the collision of the Australian and Eurasian Plates reactivated charged petroleum traps along the entire North-West Shelf and Timor Sea. The effects were greatest closest to the collisional front, in the Timor Sea. Here, dilatational reactivation of the Jurassic extensional faults produced a north-east to east-north-east trending Miocene-Pliocene fault set, which can have throws of 200-300 milli-seconds (O'Brien and Woods, 1995; O'Brien *et al*., 1996). This fault set breached the seal in many of the charged traps, such as Keppler-1, East Swan-1 and -2, and Avocet-2, resulting in the complete loss of the hydrocarbon column up the faults to the paleo-seafloor.

Whilst significant fault reactivation clearly results in catastrophic leakage of the reservoired hydrocarbons, fluid inclusion and other data (O'Brien and Woods, 1994; O'Brien and Lisk, 1995; O'Brien *et al*., 1996b) has actually suggested that some fault reactivation may favour preservation of the oil columns. For example, many of the sub-

commercial gas accumulations in the Timor Sea, such as Oliver-1 and Montara-1, previously had significant oil columns which were subsequently later displaced by gas. These traps are high integrity and have not leaked at all. In contrast, all of the commercial oil accumulations in the area, such as Challis, Jabiru and Skua, have been slightly reactivated in the Miocene-Pliocene and have all leaked. As a result, these traps have a low sealing capacity for gas (but moderate for oil), which has resulted in any later gas which entered the structure progressively bleeding off up the faults, rather than displacing the oil column.

A similar situation appears to apply to the Carnarvon Basin. There, the primary problem is the drilling of sub-commercial gas accumulations, rather than commercial oil accumulations. Such variability occurs on a very small scale. Work by O'Brien and Lisk (1995) has, however, demonstrated the many of these sub-commercial gas fields, such as Pepper in the Barrow Sub-basin, previously possessed significant oil legs which were subsequently displaced by a later gas charge. These traps are often four-way, dip-closed anticlines which are unreactivated and in which no possibility of leakage exists. As in the Timor Sea, the oil accumulations, such as South Pepper, North Herald and Harriet, are all slightly reactivated, which has prevented later gas flushing.

Hence, it appears that in both the Timor Sea and Carnarvon Basin, the most prospective traps for oil may often be actually slightly 'leaky':- these have a low sealing capacity for gas but high for oil, which reduces the likelihood of late-stage gas displacement. It is the relative balance between hydrocarbon charge history and trap integrity which ultimately determines the nature of the accumulation which develops. Consequently, any means by which the relative integrity of the traps could be established pre-drill could greatly reduce the risk of drilling gas versus oil accumulations (see later section on 'HRDZ's').

BONAPARTE BASIN

Regional Geology

Much of the early exploration in the Bonaparte Basin focused on the Petrel Sub-basin, a northwest-trending rift basin located within the Joseph Bonaparte Gulf (**Figure I-1**). This sub-basin was initiated by rifting in the late Middle Devonian to Early Carboniferous (Blevin *et al*., 1996a, b) and contains numerous salt diapirs and other salt related structures. Two large, but undeveloped, gas-condensate accumulations (the Tern and Petrel Fields) have been discovered within the Petrel Sub-basin. Both fields are reservoired in Late Permian sandstones within the Gondwanan Petroleum Supersystem.

Further offshore, the Petrel Sub-basin is orthogonally overprinted by northeast and east-northeast-trending tectonic provinces (O'Brien *et al*., 1993) which traditionally have been related to the rifting and ultimate break-up of Gondwana in the Middle Jurassic. One of these provinces is the Malita Graben, an east-northeast-trending depocentre which defines the known north-western limit of the Petrel Sub-basin. The Malita Graben may be a Late Jurassic source rock depocentre and 'kitchen' for the east-northeast-trending Sahul Platform, which is located immediately to the northwest (**Figure II-2**). The Sahul Platform comprises most of Area 'A' of the joint Australian-Indonesian Zone of Co-operation (ZOC) which has recently been the locus of highly successful exploration. As well as the major discoveries at Laminaria-1, Elang-1 and 2, Kakatua-1 and Bayu-1, two earlier non-commercial gas-condensate accumulations, Sunrise-1 and Troubadour-1, are located on its far eastern flank. The Sahul Platform was structurally positive throughout much of the Late Jurassic, with sediments of this age being thin due to nondeposition and/or erosion (Botten and Wulff, 1990).

The south-west margins of both the Sahul Platform and the Malita Graben are defined by the northwest-trending Sahul Syncline (**Figure II-2**). Immediately to the south-west of this is the Vulcan Sub-basin, a northeast-trending, Late Jurassic depocentre flanked by two Permo-Triassic blocks, the Londonderry High and the Ashmore Platform (Pattillo and Nicholls, 1990). In the early to mid-1980's, Jabiru, Challis and Skua were three commercial oil fields discovered in the Vulcan Sub-basin (**Figure II-3**). Apart from these, only small non-commercial oil or gas accumulations have been encountered at Bilyara-1, Keeling-1, Montara-1, Oliver-1, Talbot-1 and 2, Tahbilk-1 and Puffin 1-4. Both the Jabiru and Skua Oil Fields are located on prominent intra-sub-basin terraces and produced from sands which range in age from Early to Late Jurassic (MacDaniel, 1988; Osborne, 1990). In contrast, both the Challis Oil Field and the non-commercial Talbot accumulations are reservoired in Triassic sands.

Quite disparate tectonic mechanisms have been put forward to explain the origin of structures within the Vulcan Sub-basin, including strike-slip (Warris, 1973; Nelson, 1989), extensional (Woods, 1988, 1992) and extensional/oblique extensional (Fittall and Cowley, 1992) processes. A theory to explain both the development of original structures and their subsequent re-activation history has been developed by O'Brien (1993, 1995).

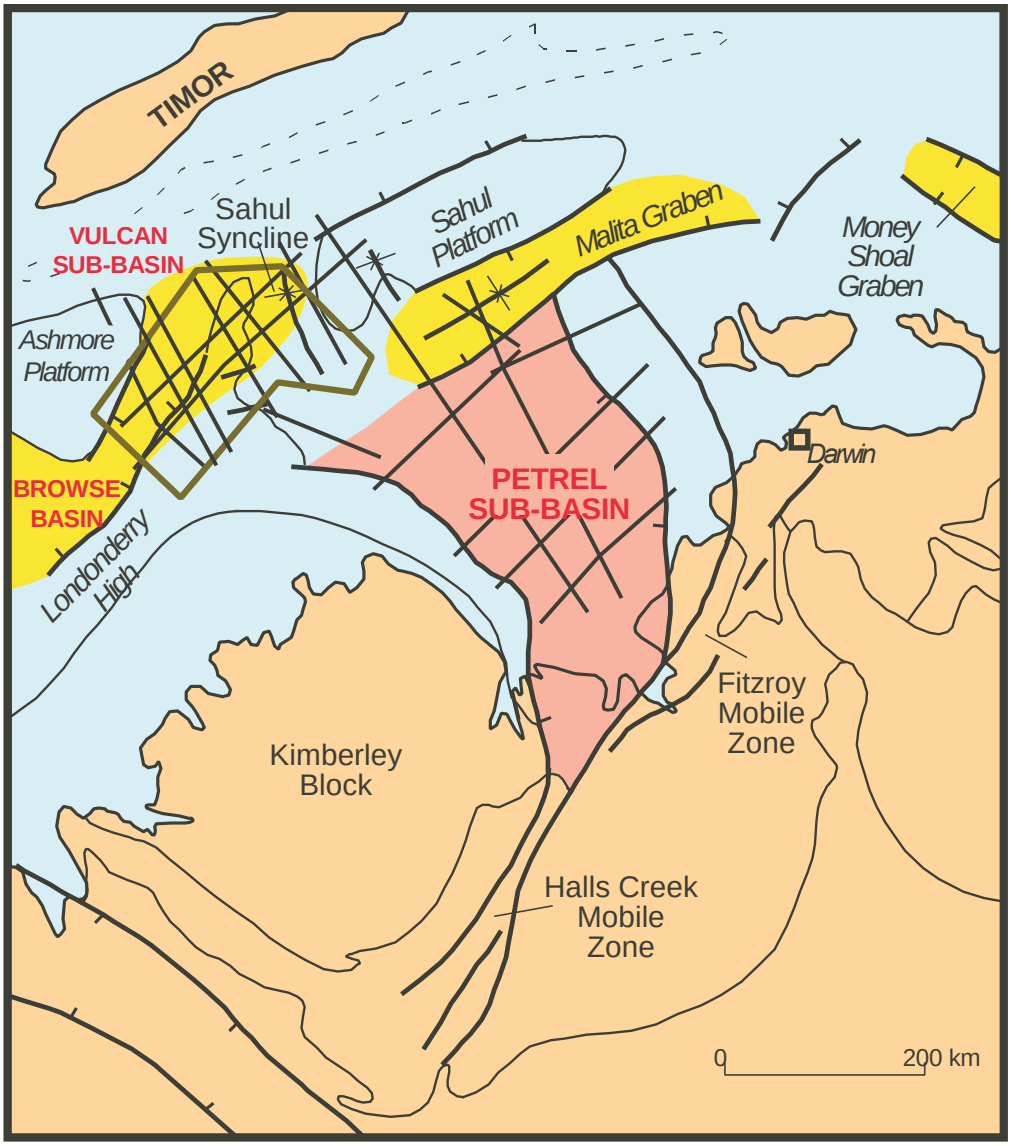


Figure II-2. Generalised Tectonic Elements Map of the Bonaparte Basin. The outlined area denotes the extent of AGSO's aeromagnetic survey which is shown in detail in Figure II-3 (after O'Brien, 1993).

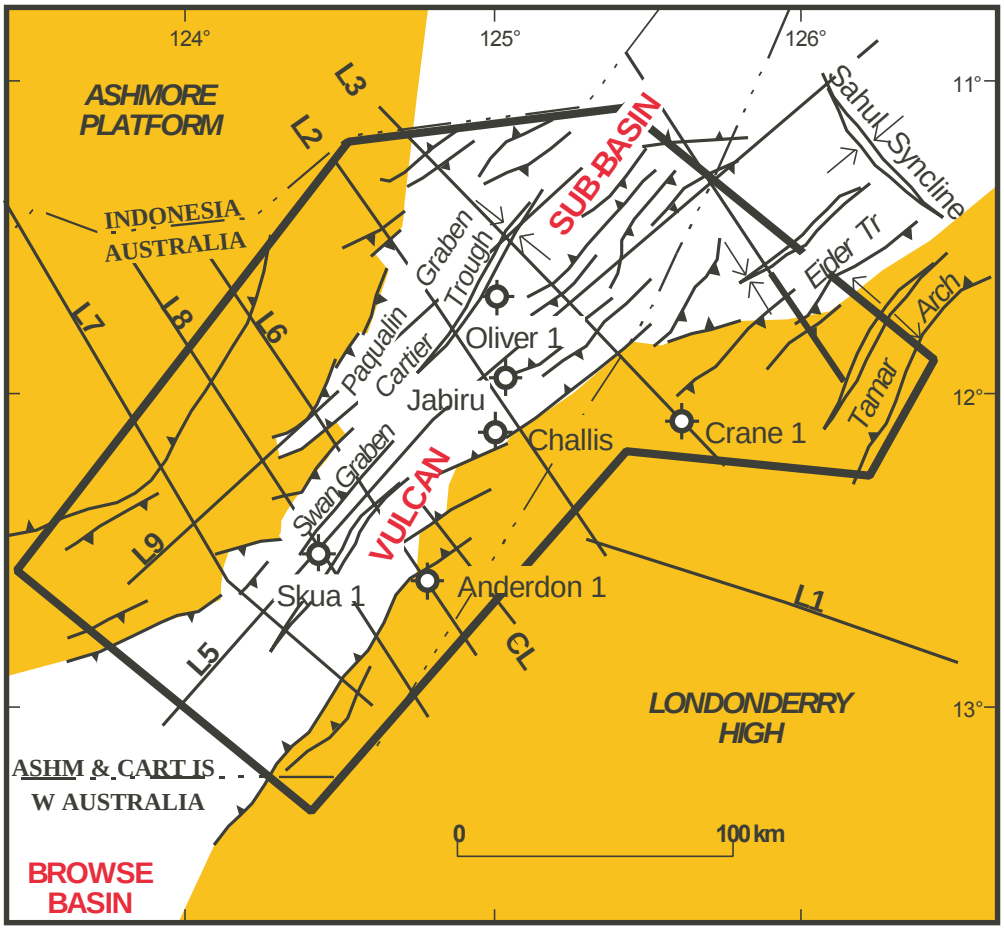


Figure II-3. Map of the Vulcan Sub-Basin and Surrounds, showing the position of AGSO's nine deep crustal seismic lines (98/1-9) and well locations (after O'Brien, 1993).

Regional Geology of the Vulcan Sub-basin

AGSO's deep crustal seismic program in the Vulcan Sub-basin, comprising seven dip and two strike lines (**Figure II-3**), showed for the first time that this sub-basin was a shallow, grossly symmetric feature, bounded on both sides by near vertical fault zones (**Figure II-4**). The most obvious feature of the deep seismic data was a very strong and relatively unstructured reflector situated 3-4 secs TWT below the Near-Top-Permian (Top Hyland Bay Formation) horizon. Magnetic and regional industry seismic data indicate that the deep event probably represents the top of a basement sequence equivalent to the Archaean and Proterozoic Kimberley Block onshore. Key features of this deep reflector are its fairly unstructured nature and that it shows no evidence of substantial rotation, as would be expected in a 'classic' rift province. It typically 'ramps' down to the northwest, being shallowest on the Londonderry High and progressively deepening under the Vulcan Sub-basin and out to the Ashmore Platform. Sediments between basement and the Top-Permian horizon are largely flat-lying, unstructured and evenly thick. Detachment surfaces, low-angle extensional faults and rotated fault blocks are absent while the faults are characteristically high-angle and often steepen with depth. In contrast, overall 'extension' achieved by faults within the Mesozoic section is < 5%, even though these same faults have traditionally been considered to reflect the principal continental extension event that preceded continental break-up and the initiation of seafloor spreading in the Jurassic. The features described above can be explained by the 'upper plate-lower plate' detachment models of Etheridge *et al*. (1988, 1990) and Lister *et al*. (1991).

A combination of deep crustal seismic data with gravity and magnetic anomaly maps has produced a regional synthesis of the tectonic history of the Bonaparte Basin and this is summarised in **Figure II-5**. Detailed discussion can be found in O'Brien (1993). However, particularly worthy of emphasis is the low strain reactivation of the deeper architecture during the Mesozoic, for this strongly shaped the structures which are being actively explored in the Timor Sea. In this area, three main reactivation events took place in the Mesozoic and include compression in the Middle Triassic to Early Jurassic, extension in the late Middle to early Late Jurassic and compression in the Late Jurassic to Early Cretaceous thereby producing a plethora of structures. The extensional event, while of small magnitude, was critical to the petroleum prospectivity of the region, as the extensional/transtensional reactivation of the older fault sets strongly defined the Vulcan Sub-basin and produced rapidly subsiding grabens, at the same time as sea level was rising rapidly due to the combined effects of eustatic and post-break-up thermal subsidence processes. This allowed source rock deposition and preservation within the grabens.

There is little Jurassic extension throughout the Timor Sea (it is typically restricted to small, narrow and deep grabens such as the Swan and Paqualin Grabens), and only a thin post-Jurassic thermal subsidence phase is present. This is illustrated in an interpretation of line 89/6 across the Swan Graben showing extensive development of Late Jurassic source rocks in the Lower Vulcan Formation (**Figure II-6**).

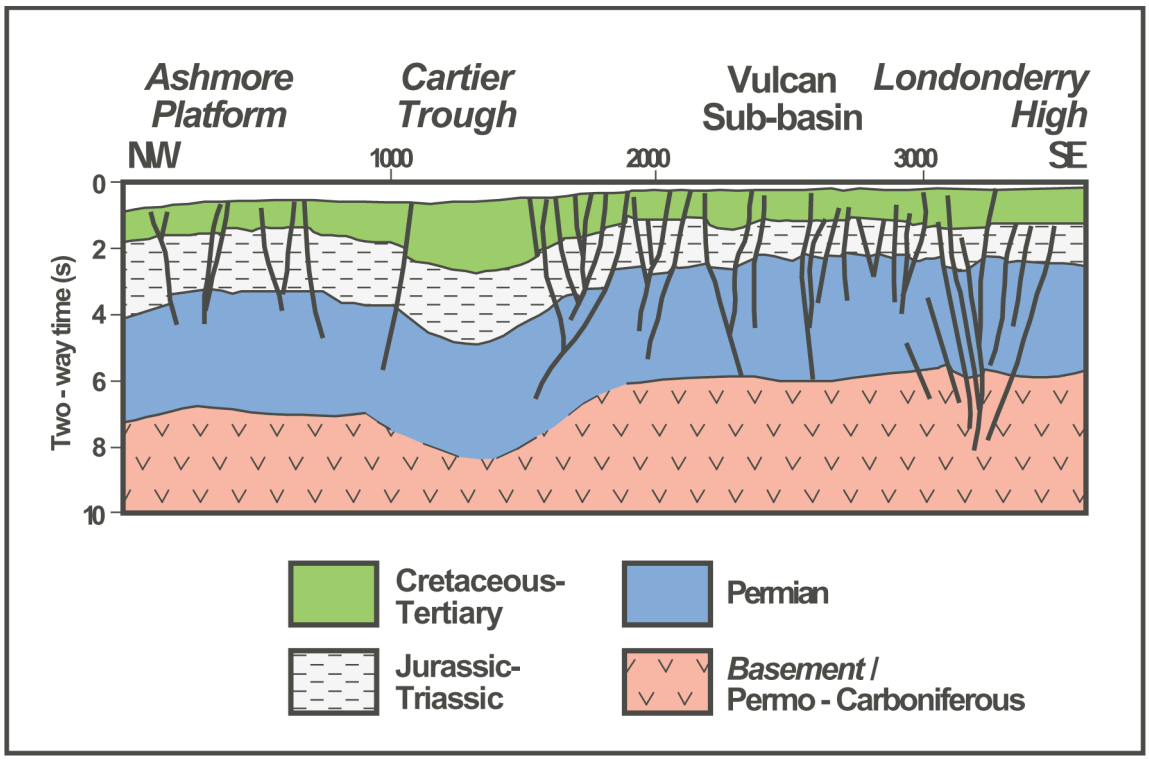


Figure II-4. A Schematic of AGSO Line 98/3 which extends northwest across the Vulcan Sub-basin (after O'Brien, 1993).

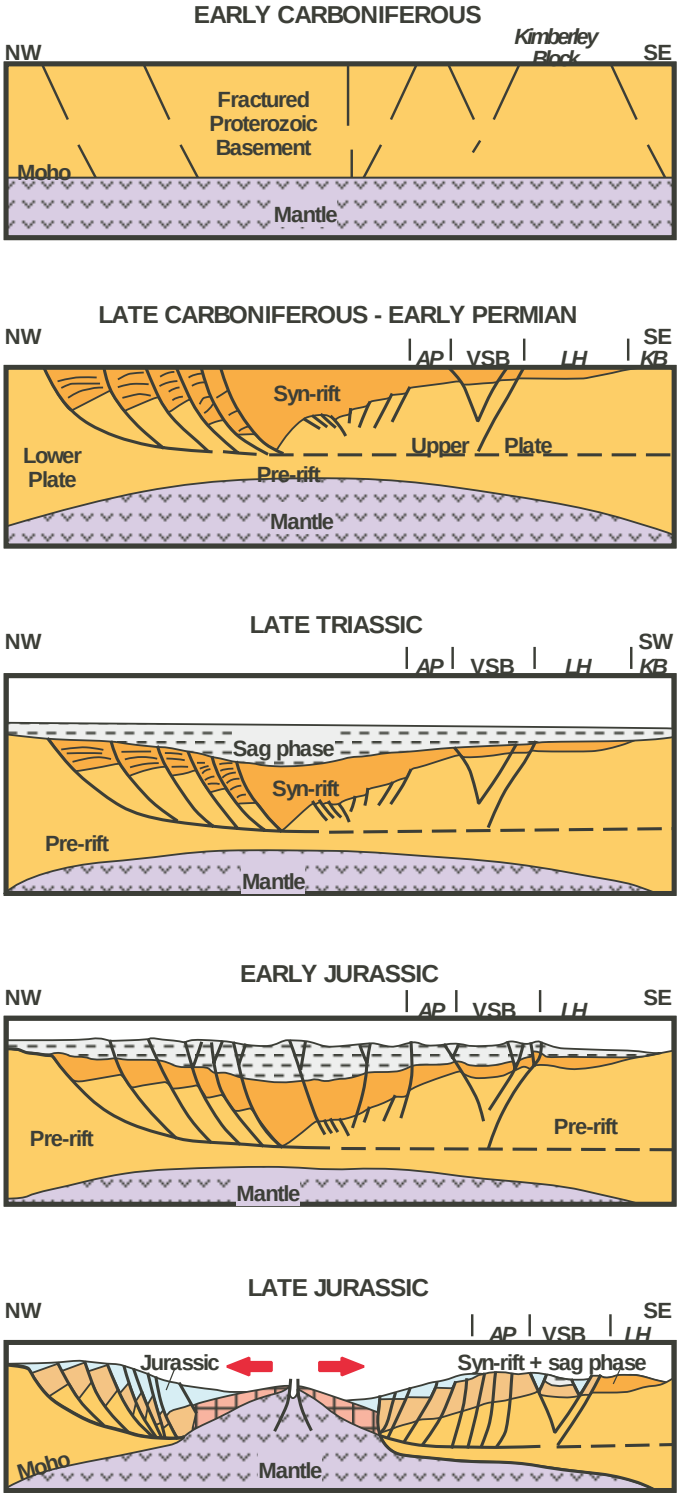


Figure II-5. Schematic Northwest-Trending Representation of the Tectonic Development of the Timor Sea Region Through Time. All sections are orientated southeast-northwest, and extend from the Timor Sea upper plate rift margin to the opposing lower plate rift margin. For the purpose of simplicity, the Petrel Sub-basin rift phase has been omitted. Abbreviations are: KB = Kimberley Block, LH = Londonderry High, VSB = Vulcan Sub-basin, AP = Ashmore Platform. Not to scale. After O'Brien (1993).

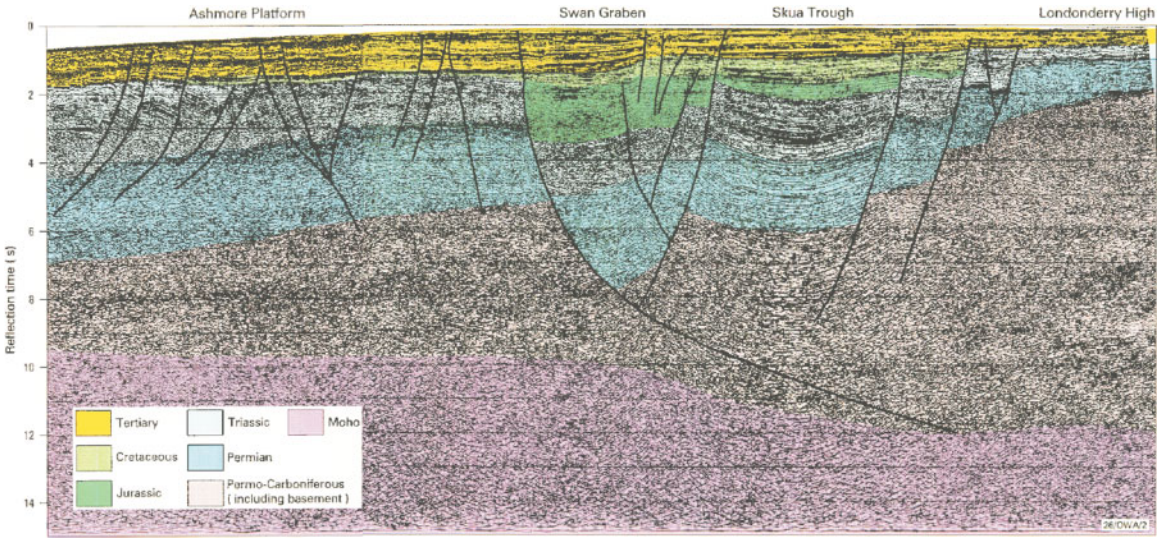


Figure II-6. An interpretation of line 98/6 Across the swan Graben showing extensive development of putative Late Jurassic Lower Vulcan Formation source rocks.

It appears that during the Permo-Carboniferous event, the crust had been so heated and thinned that only a limited amount of extension took place in the Jurassic before the crust failed (i.e., continental break-up) and seafloor spreading began. Because of the relatively small magnitude of the Jurassic rifting, the upper plate rift margin geometry, which was established in the Permo-Carboniferous, would have persisted until continental break-up in the Jurassic (i.e., the Jurassic rifting would also have been in an upper plate setting).

Stratigraphy and Petroleum Systems

A generalised Mesozoic and Cainozoic stratigraphy for the Bonaparte Basin (after Mory, 1988; 1990) is shown in **Figure II-7**, while the prospective Paleozoic is documented in the following Petrel Sub-basin section.

In the Timor Sea area (Vulcan Sub-basin and ZOC), the Triassic to Jurassic Sahul (west) and Troughton Groups (east) record sedimentation of the 'sag' phase and terminate at the Callovian break-up unconformity. The Sahul Group records mainly interbedded shale and sandstone with some carbonate sedimentation in open marine to deltaic environments. The Triassic Challis Formation, a key oil-bearing reservoir unit in the Challis Field, comprises estuarine channel sands. To the south-east, the partly co-eval Troughton Group is distinguished by its more terrestrial setting and lack of carbonates (**Figures II-7** and **II-8**). It includes, in ascending order, the Cape Londonderry, Malita and Plover Formations. The Cape Londonderry Formation is laterally equivalent to the Sahul Group (**Figure II-8**). The marginal marine to terrestrial, red sandstone and shale of the Malita Formation unconformably overlies this and is itself overlain by coarse grained sandstone with minor shale, coal and limestone of the Plover Formation. The latter is the lower oil reservoir in the Jabiru Field, as well as the reservoir in the Skua Field and the Oliver-1, Montara-1 and Bilyara-1 discoveries.

As shown in **Figure II-7**, the Flamingo Group (Mory, 1988, 1990), otherwise known as the Swan Group (Pattillo and Nicholls, 1990; O'Brien and Woods, 1995), unconformably overlies the Troughton Group. The Flamingo Group contains marine shelfal sediments including shales and sandstones of the Swan Formation (also known as the Vulcan Formation: **Figure II-9**). These latter sediments are restricted to the Vulcan Sub-basin and include a basal sand which is an upper reservoir unit for the Jabiru Field and shales reputed to be the source of the Vulcan Sub-basin oils. Above the Flamingo Group is the thick Cretaceous Bathurst Island Group comprising siltstone, mudstone, marl, limestone and sandstone (**Figure II-7**). On the Ashmore Platform, the Puffin Formation sands host the oil discovery in the Puffin Field. A thick Cainozoic section of limestone, sand and minor shale is then widely distributed over the basin.

There is little detailed analysis of the petroleum systems of the Bonaparte Basin and the nature, quality and maturity of source rocks is particularly obscure. The oldest productive source rocks are believed to be those of the Turtle and Barnett oils of the Petrel Sub-basin. These are marine siliciclastics of Early Carboniferous age assigned as either Transitional Larapintine-Gondwanan (Bradshaw *et al*., 1994) or Larapintine 4

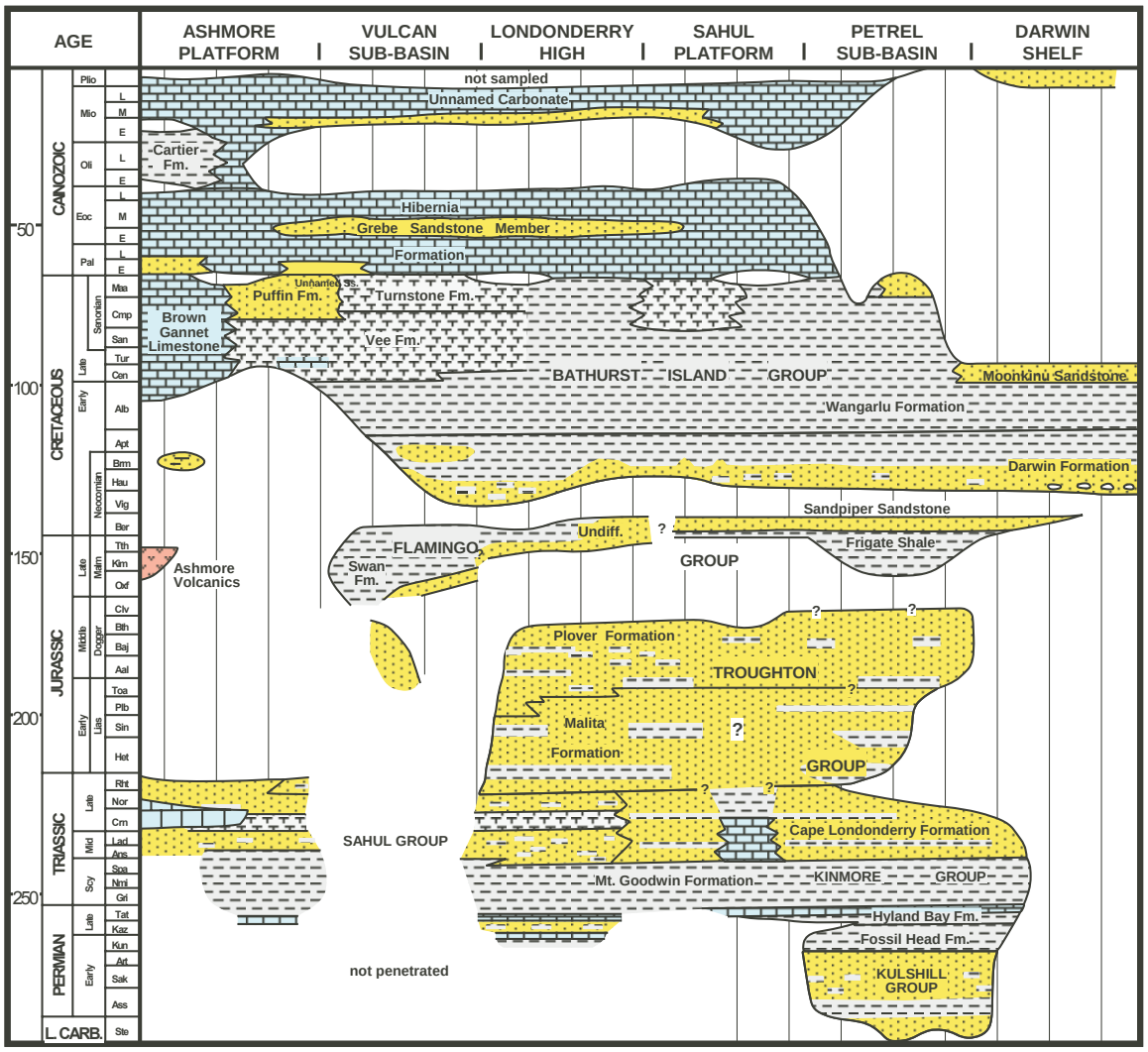


Figure II-7. Mesozoic and Cainozoic Stratigraphy for the various sub-divisions of the Bonaparte Basin (after Mory, 1990).

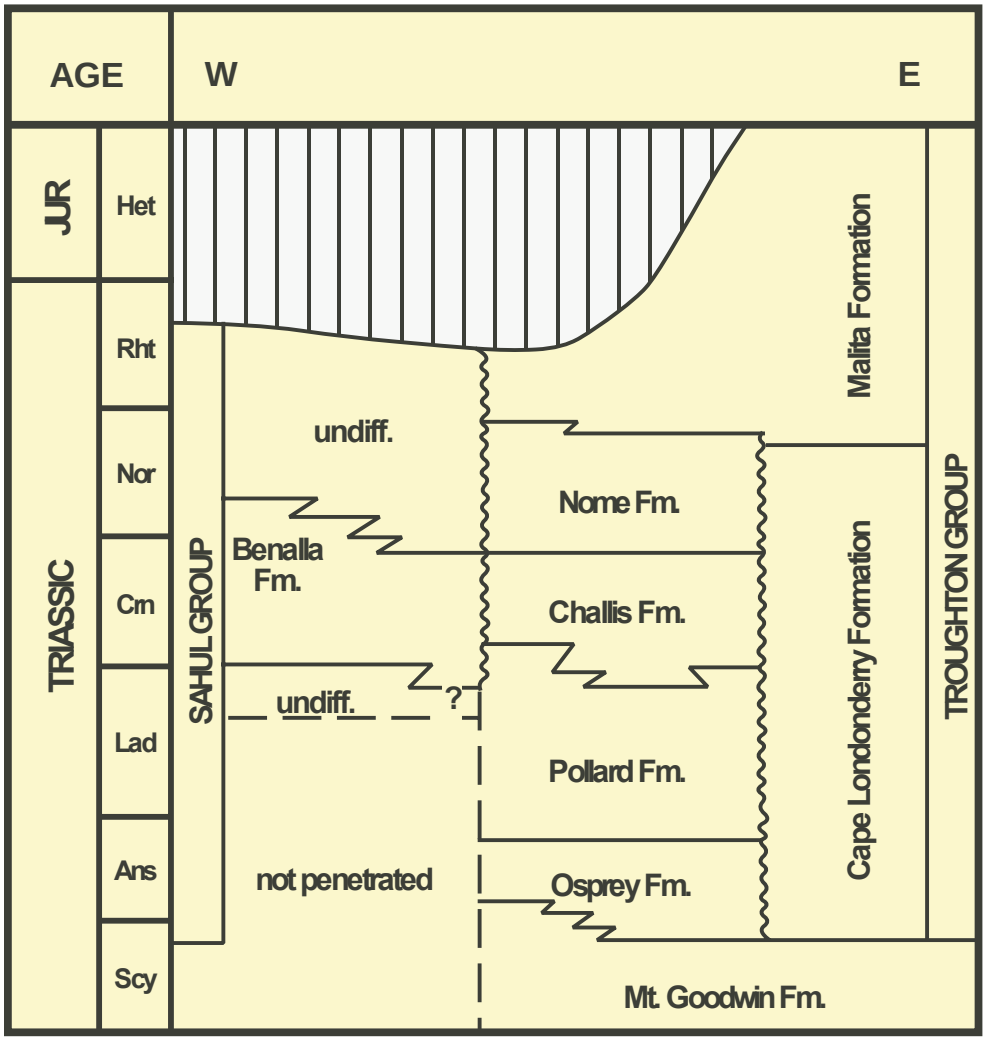


Figure II-8. Correlation of Triassic Units of the Sahul and Troughton Groups (after Mory, 1988).

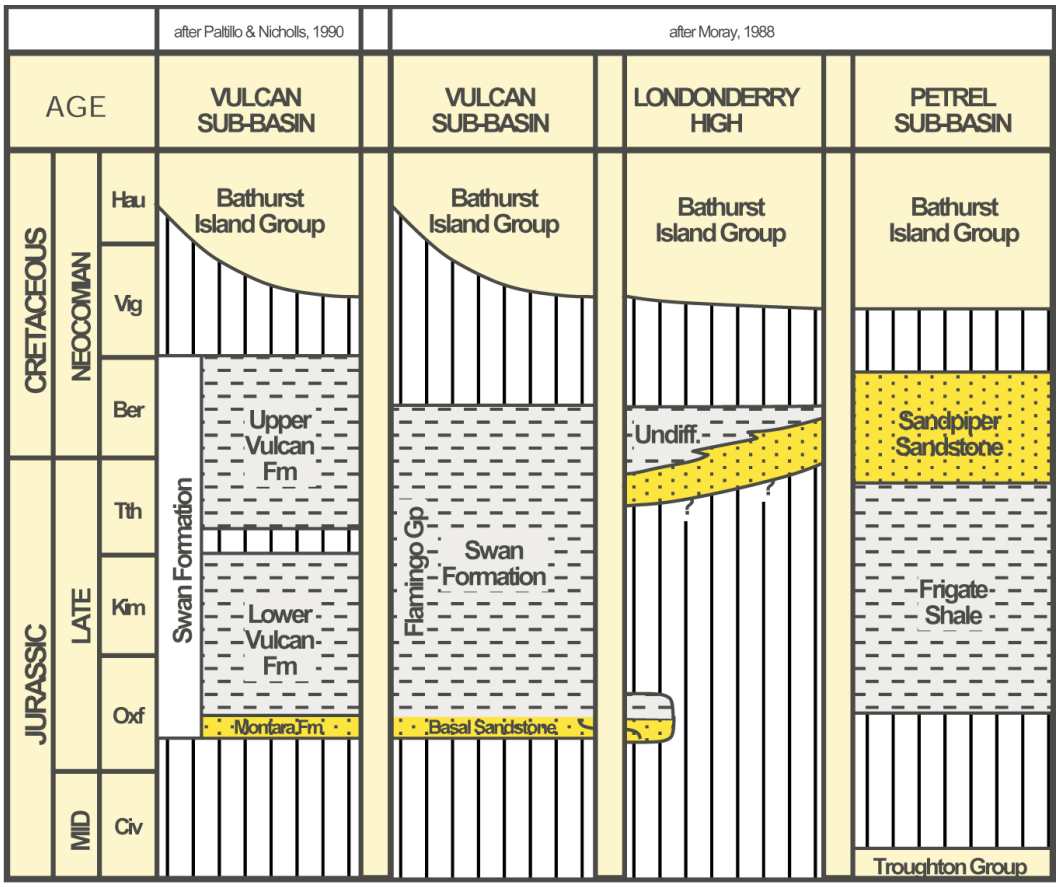


Figure II-9. Correlation of the Jurassic and Cretaceous Sediments across the sub-divisions of the Bonaparte Basin (modified from Mory, 1988 and Pattillo and Nicholls, 1990).

(Kennard *et al*., 1994). The Gondwanan Supersystem is source and host to gas and condensate of the Tern and Petrel Fields, also within the Petrel Sub-basin.

Most exploration success, however, is centred on the Jurassic and Cretaceous rocks comprising the Westralian Supersystem. While some oil-source correlations have been published (e.g., Botten and Wulff, 1990), the overall geochemical and geological analogies to the well studied system(s) in the Carnarvon and Papuan Basins are undeniable. The commercial oil accumulations appear to originate from Late Triassic to Late Jurassic source rocks, with the best quality kerogens being preserved in Late Jurassic (Oxfordian and Kimmeridgian) anoxic marine shales which were deposited in restricted troughs bordering on emergent highland areas. The Westralian successions also have a similar stratigraphy of Triassic to Cretaceous reservoirs, a Cretaceous regional seal and a thermal blanket of Tertiary carbonates which also provide additional, although discontinuous top seals. In the Vulcan Sub-basin effective Late Jurassic Westralian source rocks lie within the Flamingo Group (Swan Formation in the alternative nomenclature). These source rocks were penetrated in Vulcan-1 and Paqualin-1 where over 1200 m of moderate quality shales are recognised as being presently mature to overmature (Scott, 1994). While these and time-equivalent source rocks are only rarely encountered in exploration wells of this region, their presence and regional distribution in depocentres of the Swan and Paqualin Grabens, Cartier Trough and Sahul Syncline, is recognised in seismic sections. In a study of potential source rocks of the Timor Sea (Vulcan Sub-basin and ZOC), Botten and Wulff (1990) identified the Middle Jurassic Plover Formation and the basal Bathurst Island Formations as potential sources in addition to the aforementioned Flamingo Group. Of these, they identified kerogen-rich shales within the mid to upper Plover Formation in Avocet-1A, Flamingo-1, Tamar-1 and Gull-1 as having good oil potential. From the distribution of these rocks at the periphery of the Sahul Syncline, they inferred a moderate to deep water source facies deposited in a restricted marine embayment as having excellent source potential within the syncline proper. Paleoburial plots for Flamingo-1 suggested that the top Plover source in the Central Sahul Syncline would have been generating since the Late Cretaceous (85 Ma to present day) with the Flamingo source showing peak generation somewhat later (30 Ma to present day). These rocks in the Central Malita Graben may have been generative in the Early to Late Cretaceous (140 to 20 Ma) although there is some question about their overall source quality and hydrocarbon potential here.

Lisk and Eadington (1994) have published simulations of the timing of generation and migration of liquid hydrocarbons from the shales of the Lower Vulcan Formation in the Cartier Trough based on geohistory analysis in Octavius-1 and 2, Douglas-1, Augustus-1 and Hadrian-1. They predicted that oil generation has occurred since about 30 Ma with thresholds for oil expulsion starting about 20 Ma. Oils of differing maturities seen in inclusions in quartz overgrowths in these wells can be used to constrain the timing and course of generation and migration. Fluid inclusions containing high maturity oil are present in the Plover Formation suggesting that this is a major regional oil migration conduit. A Late Jurassic (Tithonian) sand member in the Cartier Trough contains low maturity oil consistent with local generation. These authors also report that

a 60 m paleo-oil column, similar to that in the Jabiru Field, was present but has leaked from the Octavius-2 structure and surmised that oil has been migrating from the Cartier Trough since the Miocene.

Hydrocarbon-related Diagenetic Zones (HRDZs) in the Vulcan Sub-basin

Within localised areas of the Vulcan Sub-basin, the Eocene Grebe Formation sandstones are often cemented with carbonate and recognisable on seismic sections as zones of anomalously high velocity (O'Brien and Woods, 1995: **Figure II-10**). The ^{13}C depleted isotopic signature of the carbonate within the Grebe sands indicate an origin involving the oxidation of migrating, thermogenic hydrocarbons.

Furthermore, areas of known, present-day seafloor hydrocarbon seepage, including major faults on the Skua Horst and along the Vulcan Sub-basin/Londonderry High boundary zone, are often associated with HRDZ's. Similarly, areas of known Tertiary hydrocarbon seepage, such as the residual oil columns on the Eider Horst, also contain strongly cemented Eocene sandstones. It is thought likely that most of the cementation occurred during the Late Miocene/Early Pliocene, when the Grebe sands were at a shallow depth of burial (< 300-500 m), and acting as an aquifer. The Late Miocene to Early Pliocene collision of the Australian and Eurasian Plates has resulted in breaching of many charged traps and facilitated the vertical migration of hydrocarbons through the Tertiary section. Migrating hydrocarbons could then be oxidised in the aquifer system leading to deposition of isotopically light carbonate.

Since the areal distribution of the cemented zones can effectively define hydrocarbon migration pathways, it is likely that mapping of seismically expressed HRDZ's could provide a potential predictive tool for evaluating undrilled structures. From the integration of seismic structural mapping and the characterisation of the seismic expression of the HRDZs it may be possible to determine whether an individual structure ever had a hydrocarbon column and whether or not that column is likely to be preserved. Integration of information about timing of initial generation and migration, seal integrity (in regards to Tertiary reactivation) and the probability and effectiveness of any subsequent gas flushing is seen as the key to reducing exploration risk in the Timor Sea area (O'Brien and Woods, 1995).

Regional Geology of the Petrel Sub-basin

The Petrel Sub-basin (**Figure II-11**) comprises the southern part of the Bonaparte Basin and is broadly V-shaped with a northwest-trending axis deepening into the Malita Graben to the north. It is bounded by the Lacrosse Terrace and Berkley Platform to the south-west, the Darwin Shelf to the northeast and the Sturt Block and Burt Range Shelf to the east and south-east, respectively. The sub-basin appears to be orthogonally overprinted by northeast-trending Late Paleozoic and Mesozoic tectonic elements, and its continuation northwest past the Malita Graben has, until now, been conjectural. However, deep seismic data trending northeast along the strike of the Malita Graben image a continuation of the Petrel Sub-basin, striking orthogonally to the Malita trend.

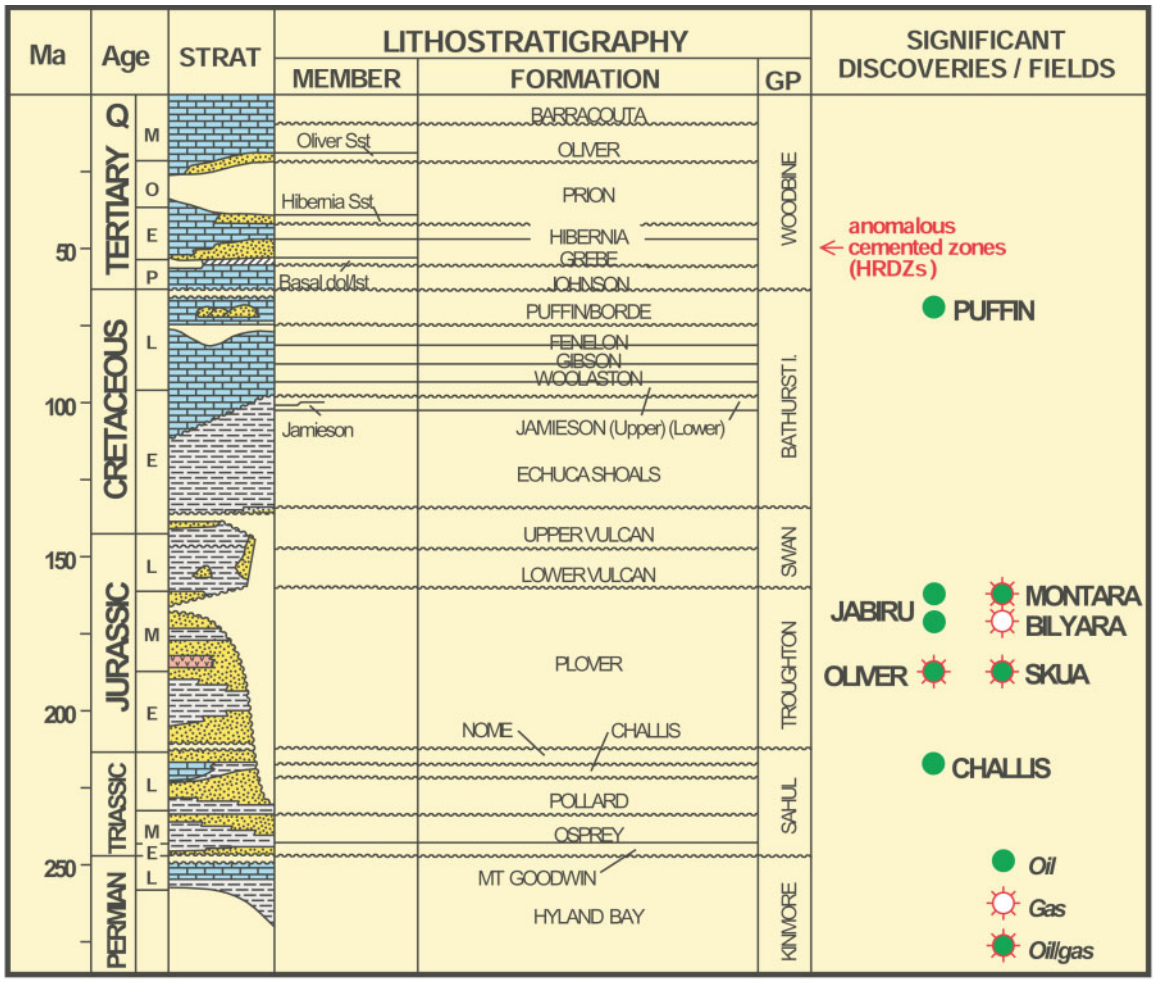


Figure II-10. Lithostratigraphy of the vulcan Sub-Basin showing position of the main oil discoveries and HRDZ's. The Swan Group in this nomenclature (Pattillo and Nicholls, 1990) is equivalent to the Flamingo Group (Mory, 1988).

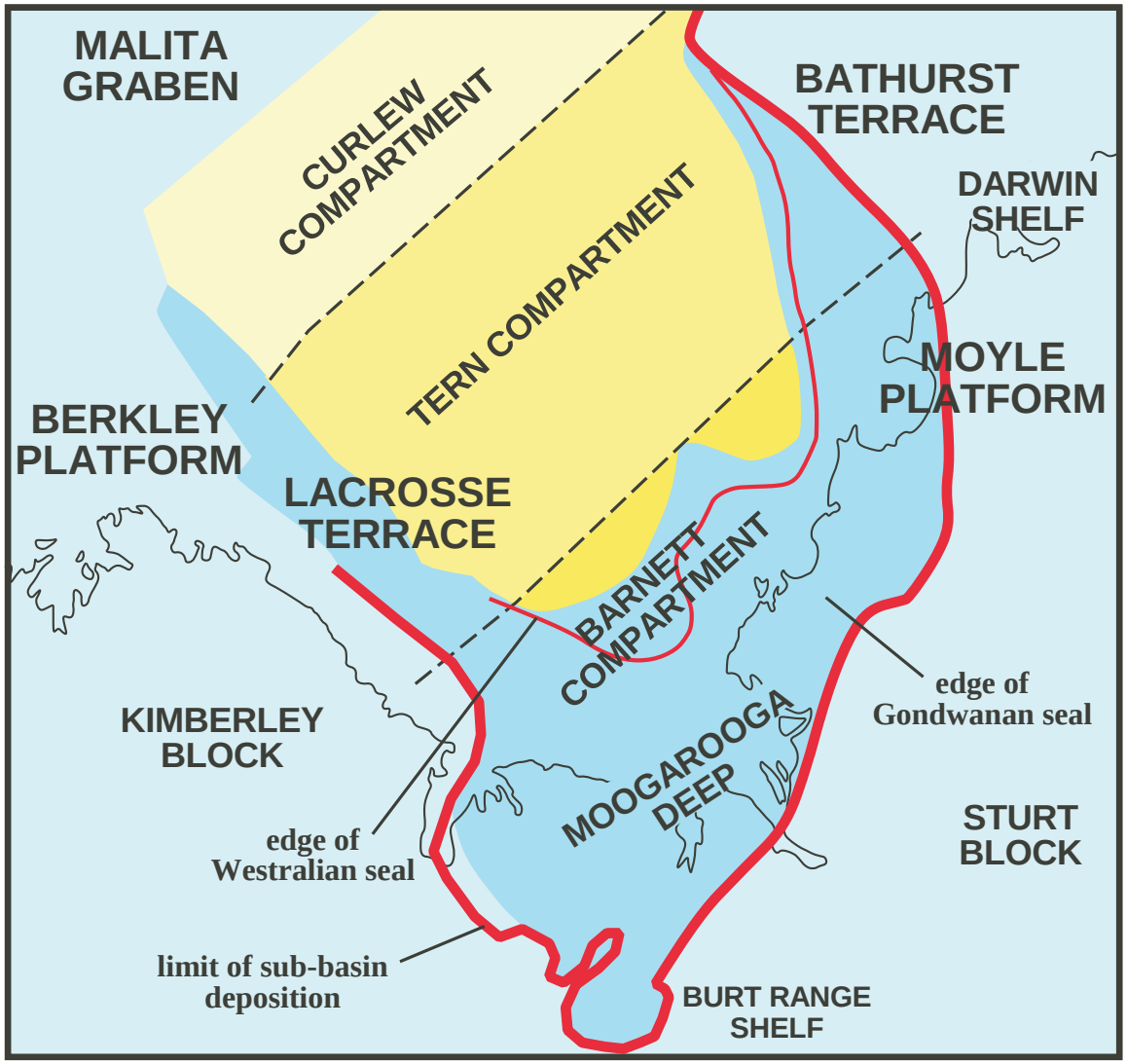


Figure II-11. Tectonic Elements Map of the Petrel Sub-Basin (after McConachie *et al*., 1996).

O'Brien *et al*. (1993) divided the Petrel Sub-basin into three northeasterly trending compartments bounded by accommodation zones. The Barnett, Tern and Curlew compartments, shown in **Figures II-11** and **II-12**, were thought to mark switches in basin polarity. More recently Blevin *et al*. (1996a, b) using gravity, AGSO deep seismic and conventional seismic data have highlighted the different structural styles of the opposing basin margins. The south-western part of the sub-basin is dominated by a northwest-trending 'large-displacement' margin and a series of rotated fault blocks. In contrast, basement (?fault-blocks) underlying the opposing eastern margin has a distinct 'ramp-like' geometry. A series of complex syn-rift packages are preserved in places on the steep upper part of the ramp. These packages may relate to an early phase of extension which occurred prior to the main late Middle Devonian (Givetian) to Early Carboniferous (Tournaisian) extension phase. Analysis of the regional gravity and seismic data suggests that an offshore, northern extension of the Halls Creek Mobile Zone (Lasseter Shear Zone) has strongly influenced the structural development of the eastern basin margin producing a prominent north-south cross-cutting structural trend extending from the Turtle-Barnett region into the Malita Graben area. Post-rift sediments (Visean and younger) thicken into the north-northwest-trending axis of the sub-basin and into the Malita Graben. In the central part of the Petrel Sub-basin, post-rift (sag-phase) sediments are over 20 km thick.

Mapping of structures within the post-rift section has shown that, in many cases, structuring within the Petrel Sub-basin took place via the reactivation of major, under-pinning Middle Devonian-Early Carboniferous rift structures, principally over the large displacement margin. Until the Late Triassic, the post-rift section in the Petrel Sub-basin was almost unstructured. In the Late Triassic to earliest Jurassic, tectonic reactivation (probably corresponding to the Fitzroy Movement in the Canning Basin) of the Petrel rift architecture produced large structures such as those which form the Tern and Petrel Gas Fields (**Figure II-13**), as well as many other structures throughout the sub-basin, and indeed the wider Timor Sea. Various models have been proposed to explain the origin of these structures, which range from compression to salt diapirism.

Stratigraphy and Petroleum Systems

There have been many revisions to Paleozoic stratigraphy of the Petrel Sub-basin (e.g., Mory 1988, 1990; Durrant *et al*., 1990; McConachie *et al*., 1995). Recent detailed seismic and biostratigraphic studies (Blevin *et al*., 1996a) have allowed further refinements to be made to the Devonian and Carboniferous stratigraphy as shown in **Figure II-14**.

Within the Petrel Sub-basin, the Cambrian Antrim Plateau Volcanics are unconformably overlain by the Carlton Group. These Cambrian to Ordovician marine sediments were deposited as part of a larger intracratonic basin in Northern Australia with probable links to the Ord and Daly River Basins. These sediments are mainly known from limited onshore exposures in the southern and south-west extremities of the basin. Salt, possibly of Late Ordovician to Middle Devonian age by analogy to evaporitic

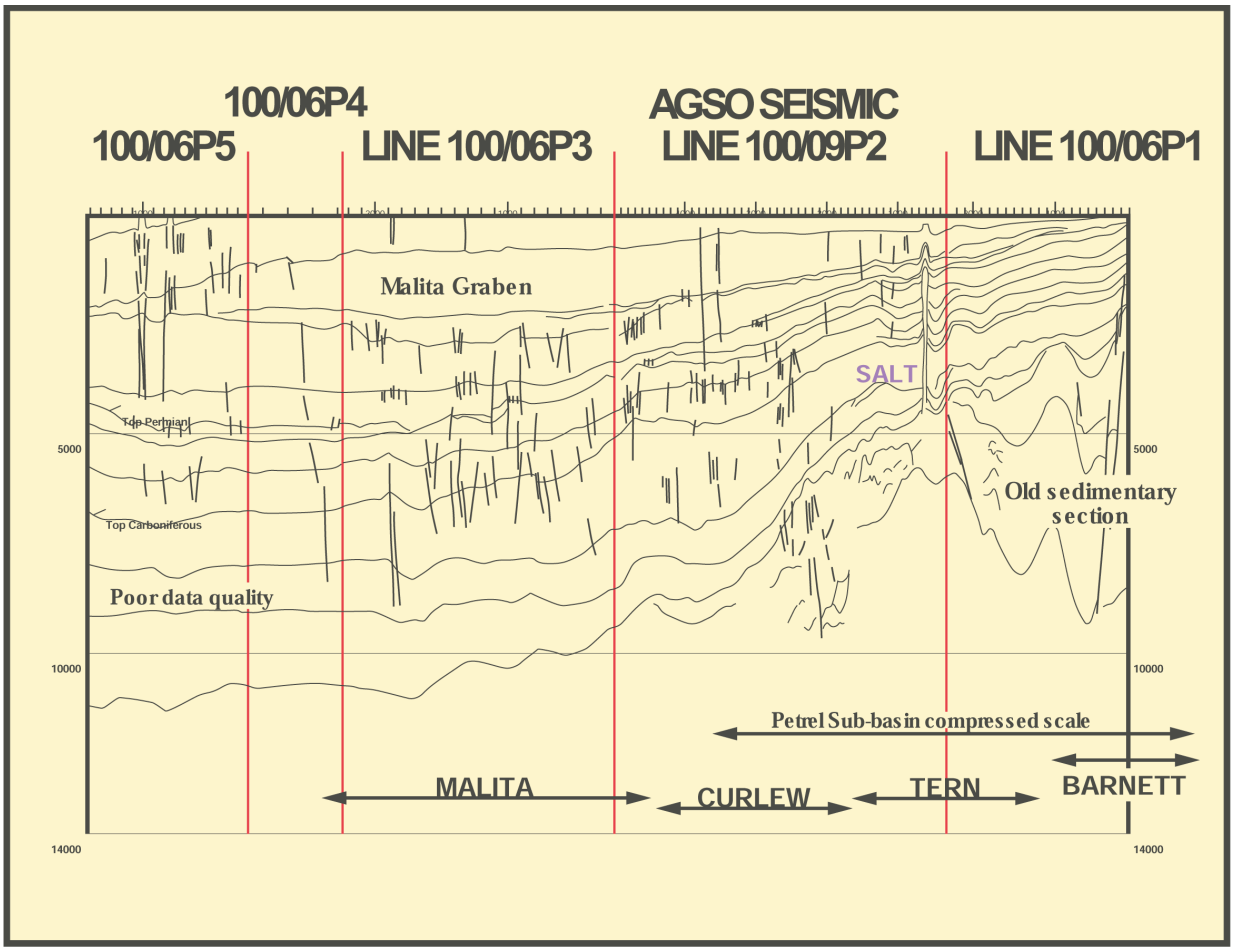


Figure II-12. NW-SE cross section through the Petrel Sub-Basin (after McConachie *et al.,* 1996).

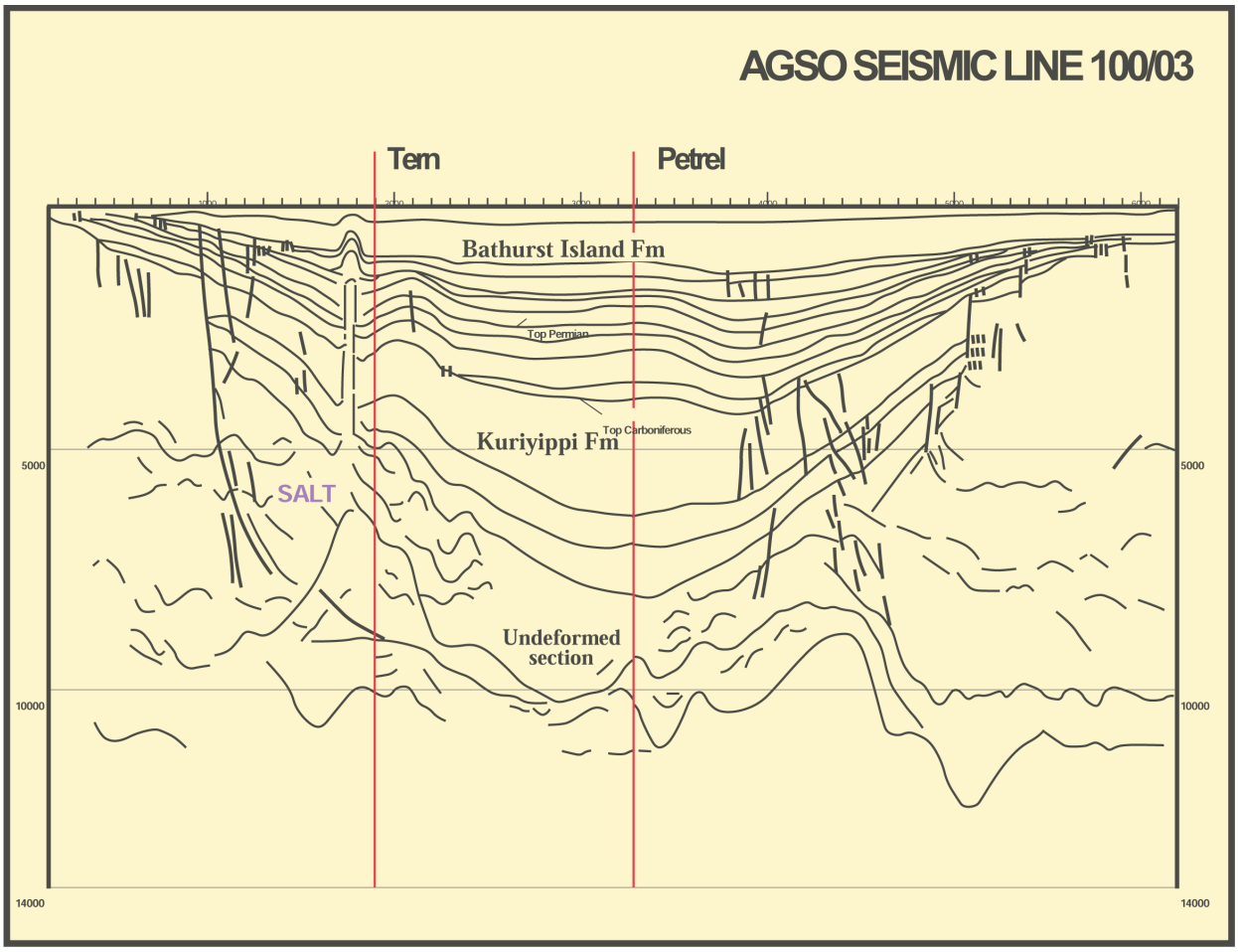


Figure II-13. NE-SW cross section through the Tern Compartment of the Petrel Sub-Basin (after McConachie *et al.,* 1996).

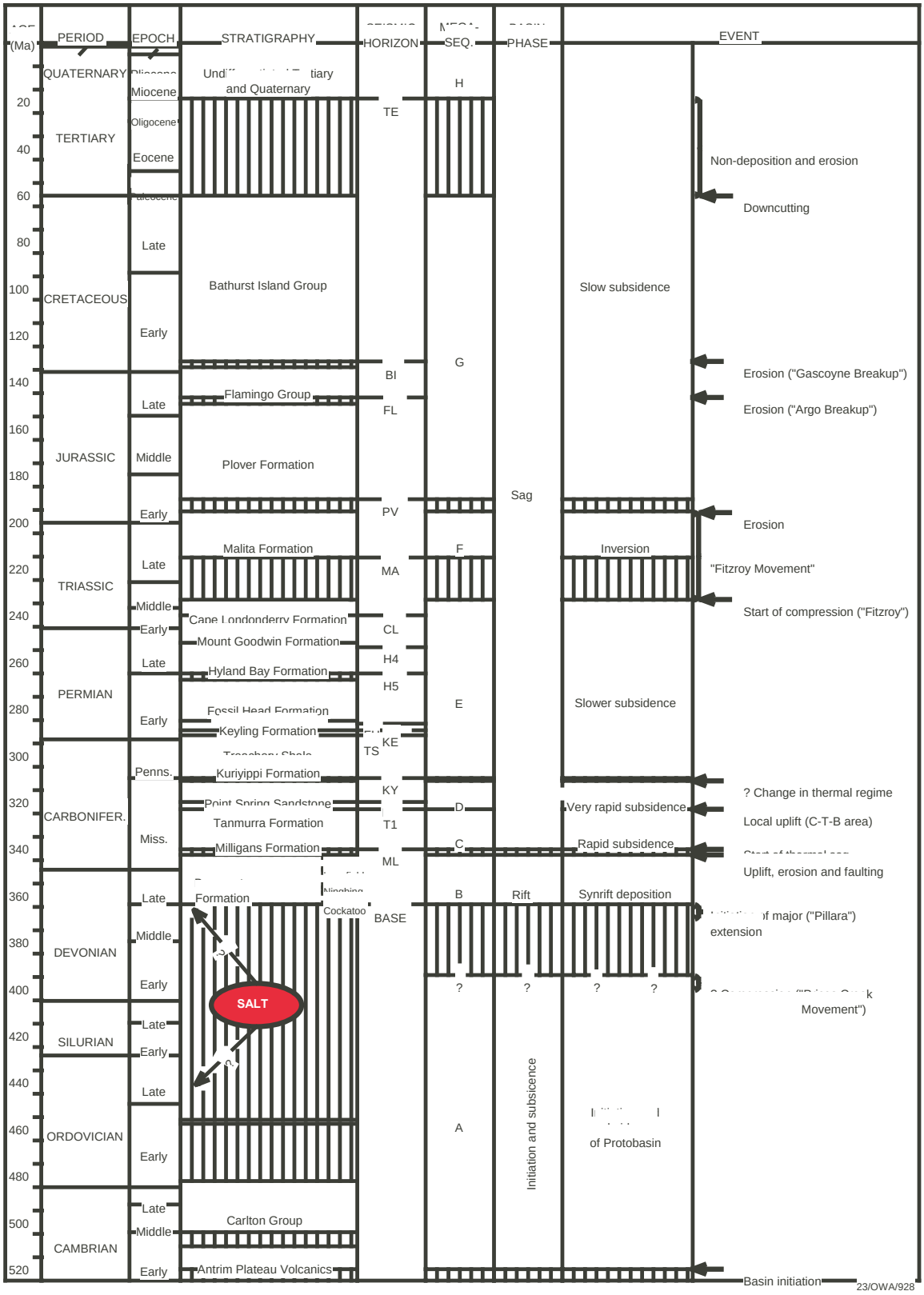


Figure II-14. Paleozoic Stratigraphy of the Petrel Sub-Basin (after AGSO Petrel Sub-basin Project, 1996).

sequences in the Canning Basin, is present in piercement structures in the central part of the sub-basin.

This older section is disconformably overlain by a thick mid-Paleozoic (late Middle Devonian-Early Carboniferous) sequence consisting of three major syn-rift units. The Cockatoo Group comprises alluvial fan, fluvial, eolian and intertidal to shallow marine siliciclastics which is followed by the reef complex carbonates and minor quartz sandstones and shales of the Ningbing and Langfield Groups.

The post-rift Weaber Group comprises anoxic marine shales of the Milligans Formation which is followed by the Tanmurra Formation and Point Springs Sandstone, a shallowing sequence of marine shelf and fluvio-deltaic sediments. These sediments were followed by up to 7 km of fluvial to glacial marine rocks of the Late Carboniferous to Early Permian Kulshill Group. Paleozoic sedimentation ended with the Kinmore Group. The Fossil Head and Hyland Bay Formations comprise siltstone, mudstone, sandstone with minor shales and coals. The latter formation is reservoir for the Tern and Petrel Gas Fields. Siltstones with minor sandstone and carbonates of the Mount Goodwin Formation mark the transition to the Mesozoic and act as a regional seal for petroleum produced in both the Larapintine, Transitional and Gondwanan Supersystems (**Figure II-15**).

In the Turtle and Barnett wells, a family of marine oils are encountered in the fluvial to glacial marine sediments of the Kulshill Group. These oils are associated with incompetent seals and meteoric waters and are variably biodegraded with low gas to oil ratios (GOR's). Deeper in the section there are related non-biodegraded oils with high GOR's reservoired within the Weaber Group's Point Springs Sandstone, Tanmurra and Milligans Formations. All these oils have apparently been sourced from marine clastic sediments and the Milligans Formation is considered the most likely origin. These oils are products of the Carboniferous period of 'transition' to higher latitude and are distinctly different to the Larapintine marine carbonate-derived oils recovered from the Late Devonian Ningbing Limestone.

The Late Permian Tern and Petrel gas and condensate accumulations are evidence for an effective Gondwanan petroleum system in the Petrel Sub-basin. McConachie *et al*. (1995) postulated that Permian deltaic sediments are the source of these hydrocarbons and presented evidence for oil-prone Permian source rocks in the north-eastern area of the sub-basin.

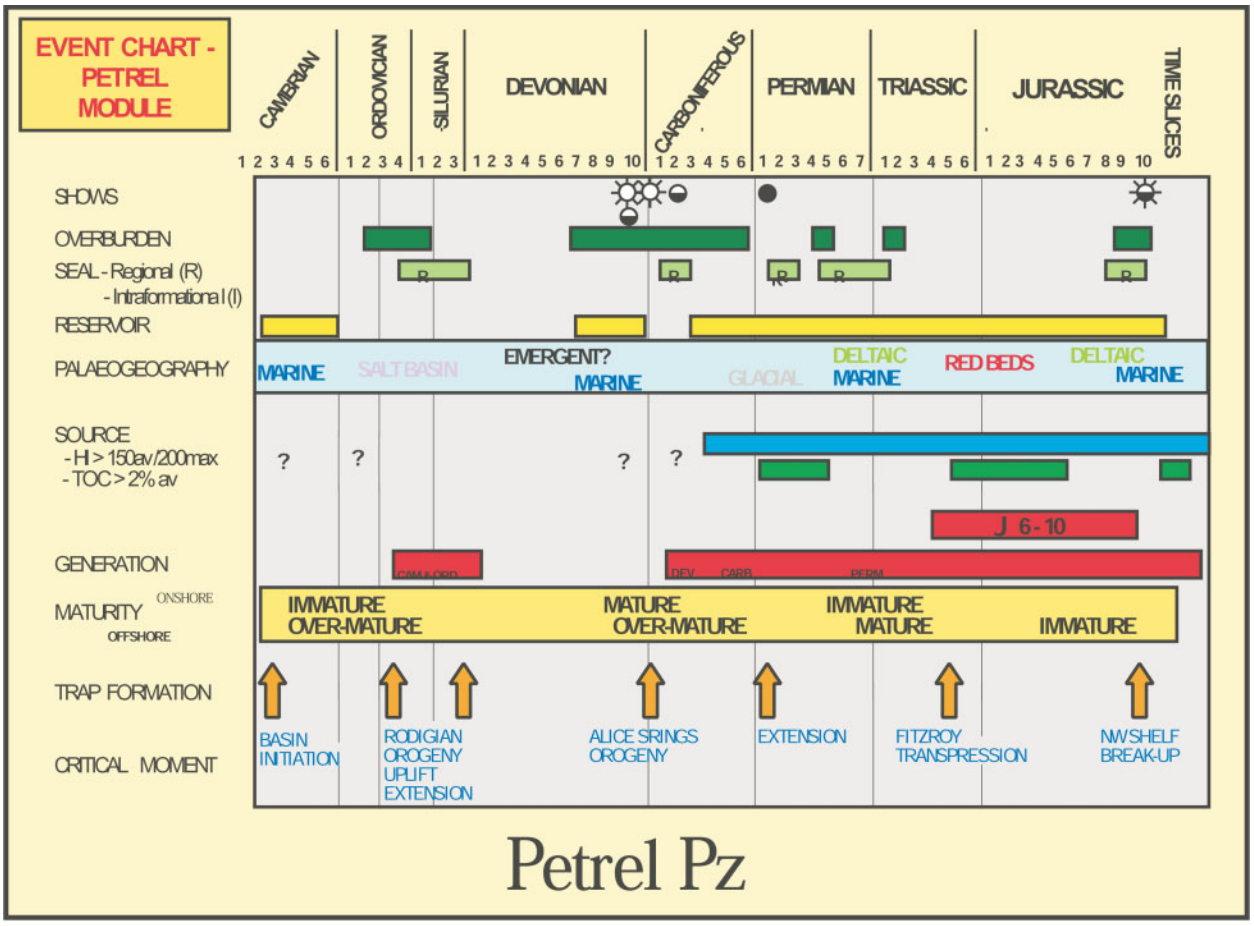


Figure II-15. AGSO-APIRA Australian petroleum Systems (APS) Event chart for the timing of respective elements of Petrel Sub-basin systems (courtesy of J. Bradshaw).

CANNING BASIN

Regional Geology

The Canning Basin is one of Australia's largest onshore basins (**Figure II-16**) and developed as a long-lived pericratonic basin with five of the six tectonic phases identified in its evolution taking place in the Paleozoic (Warris, 1993; Kennard *et al*., 1994). The earliest basin phase began with a period of extension and rapid subsidence in the Early Ordovician (Samphire Marsh Movement). Coarse clastic sediments accumulated within a series of half-grabens during this period and were succeeded by widespread marine clastic and carbonate deposits (Willara, Goldwyer and Nita Formations). As subsidence waned, thick evaporitic and playa deposits (Carribuddy Group) became widespread.

The second phase was initiated during the earliest Devonian with the Prices Creek Compressional Movement and resulted in minor folding and regional uplift. Aeolian and playa deposits accumulated during this phase. The Middle Devonian Pillara Extension marks the onset of a third phase with rifting and rapid subsidence of the Fitzroy Trough and Gregory Sub-basin. A thick carbonate reef complex developed during the period of rapid basin subsidence and was succeeded by a mixed carbonate-siliciclastic succession as subsidence waned. The reef complex was interrupted by at least two tectonic pulses (Red Bluffs and Van Emmerick Extensions), characterised by tilting and fault block movements which led to semi-regional subsidence and uplift. These pulses were marked by the influx of coarse (boulder-sized) conglomerates on the Lennard Shelf, Margaret River Embayment and Billiluna Shelf.

The Meda Transpressional Movement in the mid-Carboniferous marks the probable peak of the Alice Springs Orogeny in the Canning Basin and was a phase of compression and inversion of Devonian normal faults. An angular unconformity and deposition of syntectonic fluvial sediments of the Lower Grant Group mark this fourth phase. A fifth phase of renewed extension and rapid subsidence coincides with the onset of glaciation and led to deposition of the Upper Grant Group with a sag and widespread transgression following the glaciation. The sixth and final tectonic phase was triggered by regional dextral wrench movements in the Late Triassic to earliest Jurassic (Fitzroy Movement) and caused up to three kilometres of uplift, erosion and deposition of molasse adjacent to anticlinal uplifts.

Figure II-16 shows the major structural elements of the Canning Basin. The major northwest-trending Paleozoic extensional faults are marked by depositional troughs that contain thick sedimentary section (up to 15 km) separated by a mid-basinal arch (Broome and Crosslands Platforms) covered by a thinner (< 2 km) sediment succession. The northern trough is divided into the Fitzroy Trough and Gregory Sub-basin separated by a basement high known as the Jones Arch, and contains up the 15 km of predominantly Devonian and younger sediments. The Fitzroy Trough, formed by repeated periods of Devonian to Carboniferous extension, is bounded by the Lennard Shelf to the north and a series of fault-bounded terraces (Dampier, Jurgurra and Barbwire) to the south. These terraces, tens of kilometres wide, preserve a section

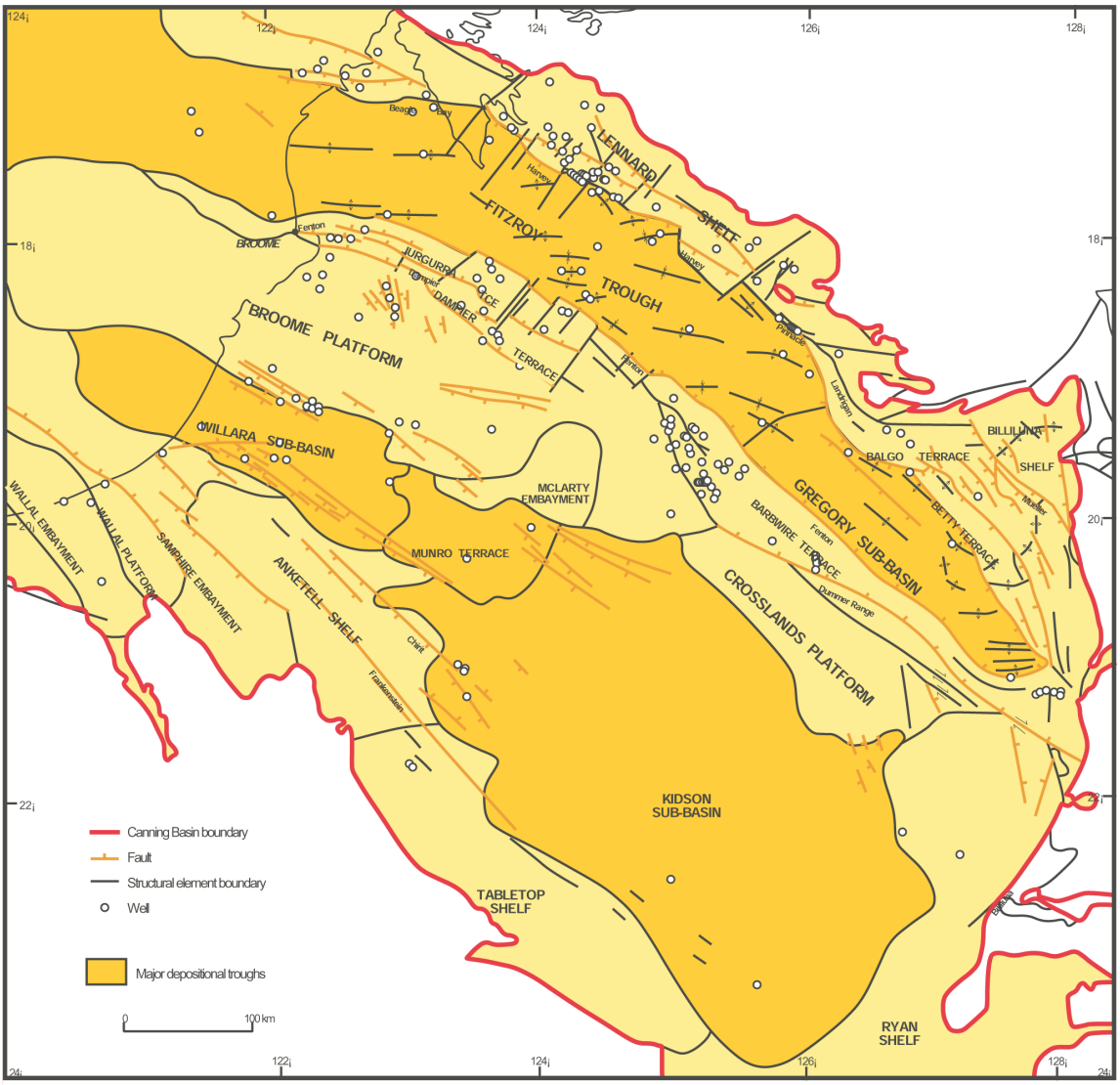


Figure II-16. Map of the Structural Subdivisions of the Canning Basin (after Kennard *et al*., 1994).

(2-4 km) of mostly Ordovician and Devonian shelf carbonates which have been a prime focus for petroleum exploration in the basin.

The southern troughs, the Willara and Kidson Sub-basins, have an Ordovician to Devonian section that includes evaporites and is unconformably overlain by Permian and younger sediments. The thick latest Devonian and Carboniferous sequences intersected in the Fitzroy Trough are absent (**Figure II-17**). The mid-basin arch (Broome Platform) is a long-lived basement high capped by a thin succession of Ordovician, Devonian and Permian rocks gently dipping to the south-east. The Broome Platform is flanked on its south-west margin by the Admiral Bay Fault Zone, a focus of exploration activity for minerals and petroleum. The Broome Platform also marks the northern boundary of the Willara Sub-basin.

Stratigraphy and Petroleum Systems

Figure II-17 shows a composite stratigraphic section for each of the Canning Basin's structural elements and also the relationships between sequence stratigraphic and lithostratigraphic units.

The mid-Paleozoic (Ordovician-Silurian) succession begins with sedimentation at the western end of the meridionally-trending tropical 'Larapintine Seaway' which connected eastwards to the Wiso, Amadeus and Georgina Basins. This succession rarely outcrops but it has been mapped seismically and encountered in 74 exploration wells. It is generally 2-3 km thick in most parts of the basin with a maximum preserved thickness of around 5 km in the Kidson Sub-basin. Initial subsidence was accompanied by sedimentation of coarse clastics over an irregular surface and within partially connected half-grabens typified by the Nambeet Formation. These sediments are overlain by a substantial thickness of shales and interbedded limestone (Willara Formation) with limestone and dolomite more prevalent toward the top of the succession (Goldwyer and Nita Formations). The succession, thickest in the Willara Sub-basin, is present in reduced thickness over the Broome Platform, the terraces of its northern margin and the southern margin of the Lennard Shelf, and is assumed to be present in the Fitzroy Trough. Many of the lithostratigraphic units within the succession are referred to as shallow marine, platform or epeiric sea deposits and comprise the richest source rocks identified in the basin. These, summarised in **Table II-1**, constitute the source elements of the Larapintine Supersystem with the *Gloeocapsomorpha prisca*-rich upper and lower Goldwyer Formations (Larapintine 2) having most potential along the Barbwire, Jurgurra and Dampier Terraces and northern Broome Platform. Most of the significant oil shows within this system (Dodonea-1, Edgar Range-1, Great Sandy-1, Percival-1, Pictor-1, Solanum-1) occur within Nita Formation carbonates although reservoir quality is generally poor in dolomitised supratidal and intertidal sediments.

Oil shales in the basal Bongabinni Formation were deposited in drainage depressions within relay ramps of the Admiral Bay Fault Zone and have excellent locally developed source richness and generative potential. However, their areal extent is not accurately known. Halite deposits in the mid to upper part of the Carribuddy Group (Minjoo and Mallowa Salt) provide a regional seal for this petroleum system.

The Larapintine 3 petroleum system is based on source elements within the Middle-Late Devonian marine shales of the Gogo Formation and the time equivalent lagoon-sabkha facies of the Mellinjerie Formation (Mirbelia Dolomite and Boab Sandstone). These organic-rich rocks, summarised in **Table II-1**, are characterised by a significant algal component and fall within a major Late Devonian source rock event recognised by Klemme and Ulmishek (1991). This system incorporates the reef complexes of the Pillara and Nullara Limestones which have been relatively extensively explored on the Lennard Shelf. The Gogo Formation is a basinal and intra-shelf marine shale facies within the Pillara Limestone and also presumed to be at depth throughout most of the Fitzroy Trough. Barbwire Terrace source rock units occur within both carbonate-anhydrite (Mirbelia Dolomite) and siliciclastic (Boab Sandstone, Gogo Formation) facies. Production within the system occurs at the Blina Oil Field which is estimated to contain about 6 Mbbl. Significant shows or flows have been recorded in Boronia-1, Ellendale-1, Janpam North-1, Mirbelia-1 and Meda-1. As with Larapintine 2, reservoir quality and preservation of accumulated petroleum are the main exploration risks. The transgressive, highstand reefs of the Pillara Limestone may have more prospectivity than the more extensively explored Nullara Limestone since they contain abundant stromatoporoids and corals which are more prone to secondary porosity development (Playford, 1984). Lowstand basin-floor and slope fans may also offer a prospective target (Jackson *et al*., 1992) and are favourably located to receive hydrocarbons from the basinal shales of the Gogo Formation.

The Larapintine 4 petroleum system is based on the occurrence of organic-rich marine shales in the Laurel Formation and encompass the Early Carboniferous Laurel and Anderson Formations. A major unconformity associated with the Meda Transpressional Movement separates this from the overlying fluvio-glacial Grant Group Sandstones of the Gondwanan Supersystem. Bradshaw *et al*. (1994) use an alternative designation (Transitional Larapintine/Gondwanan) for this Larapintine 4 system. This slightly different model arises because, in the Petrel Sub-basin, there is a major unconformity in the early Visean at the base of the Milligans Formation (age equivalent of the Anderson Formation). This unconformity is considered to mark a distinct (i.e. Transitional) period associated with the drift to higher latitude and, consequently, a different climatic regime. The occurrence of a very distinct oil type (Turtle and Barnett fields) with these sediments was further justification for allocating a separate petroleum system (Bradshaw *et al.,* 1994) as opposed to further subdivision within the Larapintine. In the Canning Basin, minor production occurs at Lloyd-1 and West Kora-1 from sandstones of the Anderson Formation and there were shows in Meda-1, West Terrace-1 and Terrace-1. Mature source rocks appear to be limited to the Fitzroy Trough while the Lennard Shelf contains poorer quality, immature to marginally mature Laurel Formation. However, these Carboniferous oils all appear to comprise a distinct group which is separate to the other Larapintine oil families derived from the Ordovician and Devonian (see later **Figure III-18**).

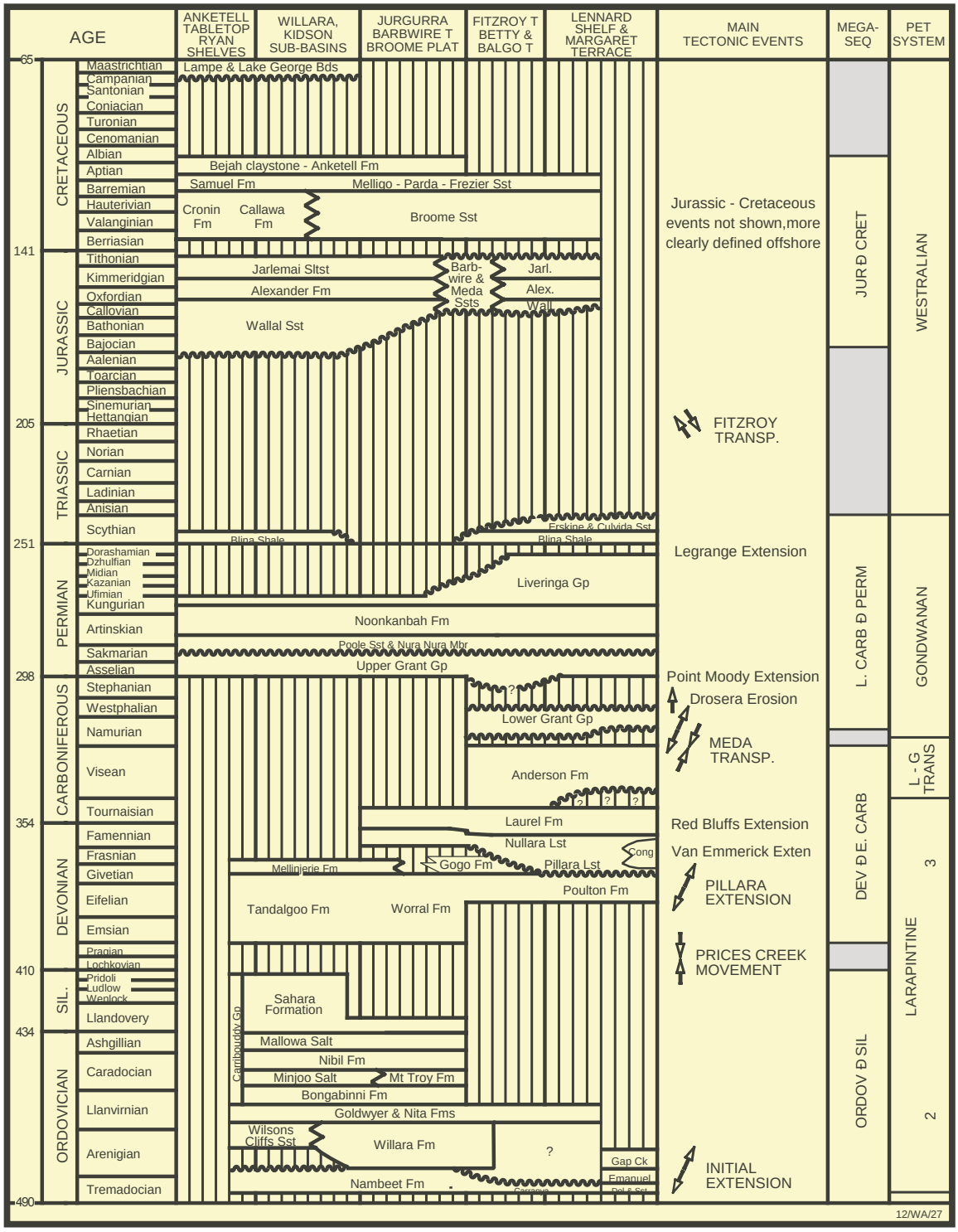


Figure II-17. Canning Basin Stratigraphic Column (modified from Kennard *et al*., 1994).

POTENTIAL SOURCE INTERVAL	TOC Min	TOC Av	TOC Max	S_2 Min	S_2 Av	S_2 Max	HI Min	HI Av	HI Max	NO. of SAMPLES TOC	NO. of SAMPLES S_2	#
GONDWANAN												
Noonkanbah	1.02	2.51	4.56	0.19	1.21	5.04	13	43	120	48	38	10
Poole	0.58	2.65	14.33	0.03	2.67	19.30	3	68	148	22	22	8
Grant Shales	0.10	0.64	7.54	0.01	1.30	37.34	2	59	495	136	62	24
LARAPINTINE 4												
Anderson	0.03	0.56	3.30	0.00	0.31	1.64	4	39	152	208	102	13
Laurel	0.14	0.80	4.84	0.10	0.75	20.29	7	65	418	214	106	22
LARAPINTINE 3												
Luluigui	0.08	0.43	1.25	0.10	0.19	0.33	9	49	113	182	26	6
Clanmyer	0.13	0.34	1.60	-	0.08	-	-	5	-	8	1	3
Gogo	0.41	1.49	4.11	0.15	1.64	5.06	51	136	280	26	17	6
Mellinjerie	0.03	0.78	2.41	-	2.05	-	-	85	-	4	1	4
`Merbelia'	1.80	2.38	4.00	3.71	8.93	12.11	277	390	610	4	4	4
`Boab Sst'	0.99	2.45	3.69	0.49	1.90	4.68	39	70	127	3	3	2
Gogo[1]	0.45	2.26	8.08	0.07	3.99	16.27	9	165	532	35	33	20
LARAPINTINE 2												
Bongabinni	3.88	32.90	54.30	12.70	116.22	174.79	321	352	417	5	5	1
Carribuddy	0.52	0.85	1.28	1.3	3.53	6.26	250	379	489	3	3	2
Upper Goldwyer												
Barbwire Terrace												
	0.46	2.01	6.40	1.39	12.99	52.96	288	599	901	34	34	5
Eastern Broome Platform - Dampier - Jurgurra Terrace												
Crystal Ck.-1	0.53	0.59	0.62	1.12	1.16	1.20	193	202	211	3	2	1
Matches S.-1	0.53	1.38	1.77	1.44	6.98	9.93	166	241	285	4	3	1
McLarty-1	1.10	1.72	2.00	2.30	2.90	3.40	142	173	246	9	9	1
Lower Goldwyer												
Barbwire - Dampier - Northern Broome Platform												
	0.58	1.67	4.70	0.46	2.43	7.86	58	141	254	82	82	11
Kidson Sub-basin												
Kidson-1	1.50	2.47	3.80	5.80	8.39	11.00	259	349	550	10	10	1
Wilsons Cl.-1	0.37	0.99	3.21	0.20	0.94	2.96	27	88	243	6	6	1
Willara												
Jurgurra Terrace												
Matches S.-1	0.82	1.47	2.11	0.93	2.19	3.21	113	143	164	3	3	1
Broome Platform												
Canopus-1	0.70	0.96	1.40	0.37	0.77	1.09	49	80	95	5	5	1
McLarty-1	1.02	1.09	1.16	0.28	0.29	0.29	25	26	27	2	2	1
Munro terrace												
Pegasus-1	0.70	0.80	0.90	0.30	0.34	0.37	41	42	43	2	2	1
Setaria-1	0.37	0.45	0.57	0.30	0.50	0.80	81	108	140	3	3	1
Nambeet												
Broome Platform												
Edgar R.-1	1.32	1.44	1.52	0.19	0.22	0.25	14	15	16	3	3	1
Hedonia-1	0.44	0.60	1.09	0.05	0.20	0.49	11	33	75	15	15	1
Hilltop-1	0.43	0.60	0.73	0.02	0.15	0.18	4	13	28	7	7	1
Dampier Terrace												
Pictor-1	0.52	0.67	0.84	0.03	0.06	0.07	4	8	11	4	4	1
Lennard Shelf												
Gap Ck.-1	0.68	0.75	0.81	1.39	1.67	1.94	185	223	245	3	3	1
Tappers In.-1	0.28	0.51	1.10	0.11	0.35	1.74	13	38	124	12	12	1

Table II-1. Selected source rock data: Larapintine and Gondwanan Petroleum Systems. Data from AGSO Orgchem database (as of March 1994). # Number of wells sampled

Two Gondwanan petroleum systems (Gondwanan 1 and 2) are recognised in Western Australia with the mid-Carboniferous Meda Transpressional Movement marking the end of the Larapintine regime and a switch from marine to predominantly terrestrial organic matter in the sediments. Fluvial and glacigene clastics of the Grant and fluvial to marine clastics of the overlying Permian Poole-Noonkanbah-Liveringa succession have been assigned to the Gondwanan 1 petroleum system with the major potential source intervals forming part of a global, Late Carboniferous-Early Permian source period (Warris, 1993; Klemme and Ulmishek, 1991). Although they are relatively rich in organic matter, these units are thermally immature except in the Gregory Sub-basin and depocentres along the southern margin of the Fitzroy Trough. Marine shales of the Upper Grant Group are locally organic-rich but have low generative potential. Hydrocarbons are reservoired within the Upper Grant Group sediments, namely those encountered in Boundary-1, Sundown-1 and West Terrace-1, although these are widely believed to have been sourced from shales within the Laurel Formation of Larapintine 4.

Sediments of the Gondwanan 2 petroleum system are not thought to have potential in the onshore Canning Basin since the Early Triassic Blina Shale source unit is immature.

Comprehensive studies (Kennard, 1995) have been conducted to establish maturation models and event timing for the Larapintine and Gondwanan Supersystems as shown **Figures II-18, II-19** and **II-20**. This analysis indicates that the Paleozoic organic-rich intervals attained peak maturity and expelled the bulk of their hydrocarbons during major subsidence-sag phases in the Ordovician-Silurian, Middle Devonian-Early Carboniferous and Early Permian-Triassic. Little or no additional generation has occurred since the Triassic and therefore any undiscovered hydrocarbon accumulations must be in traps that were present at this time and protected by adequate and competent seals which survived subsequent tectonic movements.

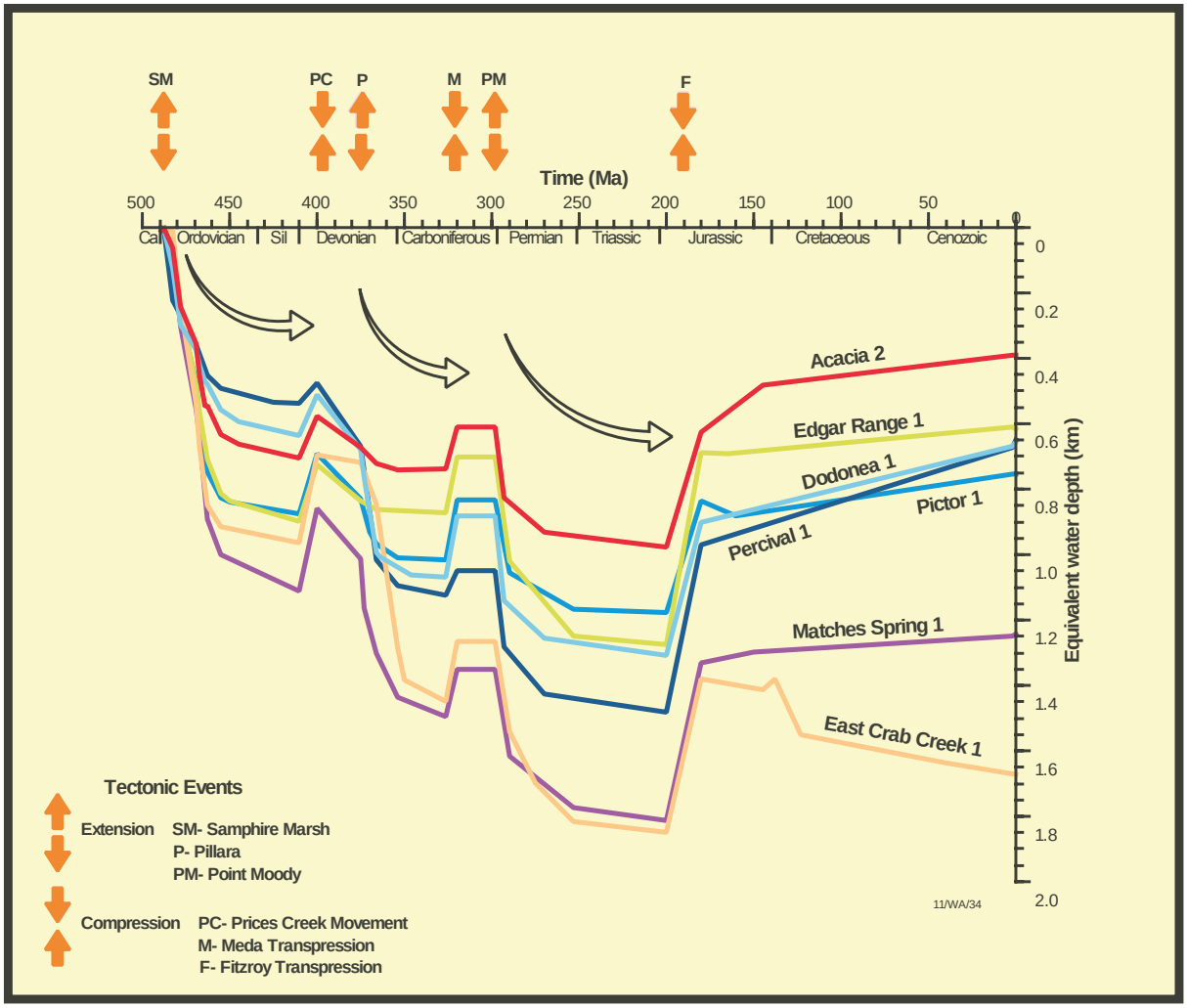


Figure II-18. Stripped-Basement Subsidence Curves for wells modelled on the Jugurra-Dampier-Barbwire Terraces, showing major tectonic events and subsidence-sag phases (curved arrows) that controlled thermal maturation of source intervals (after Kennard, 1995).

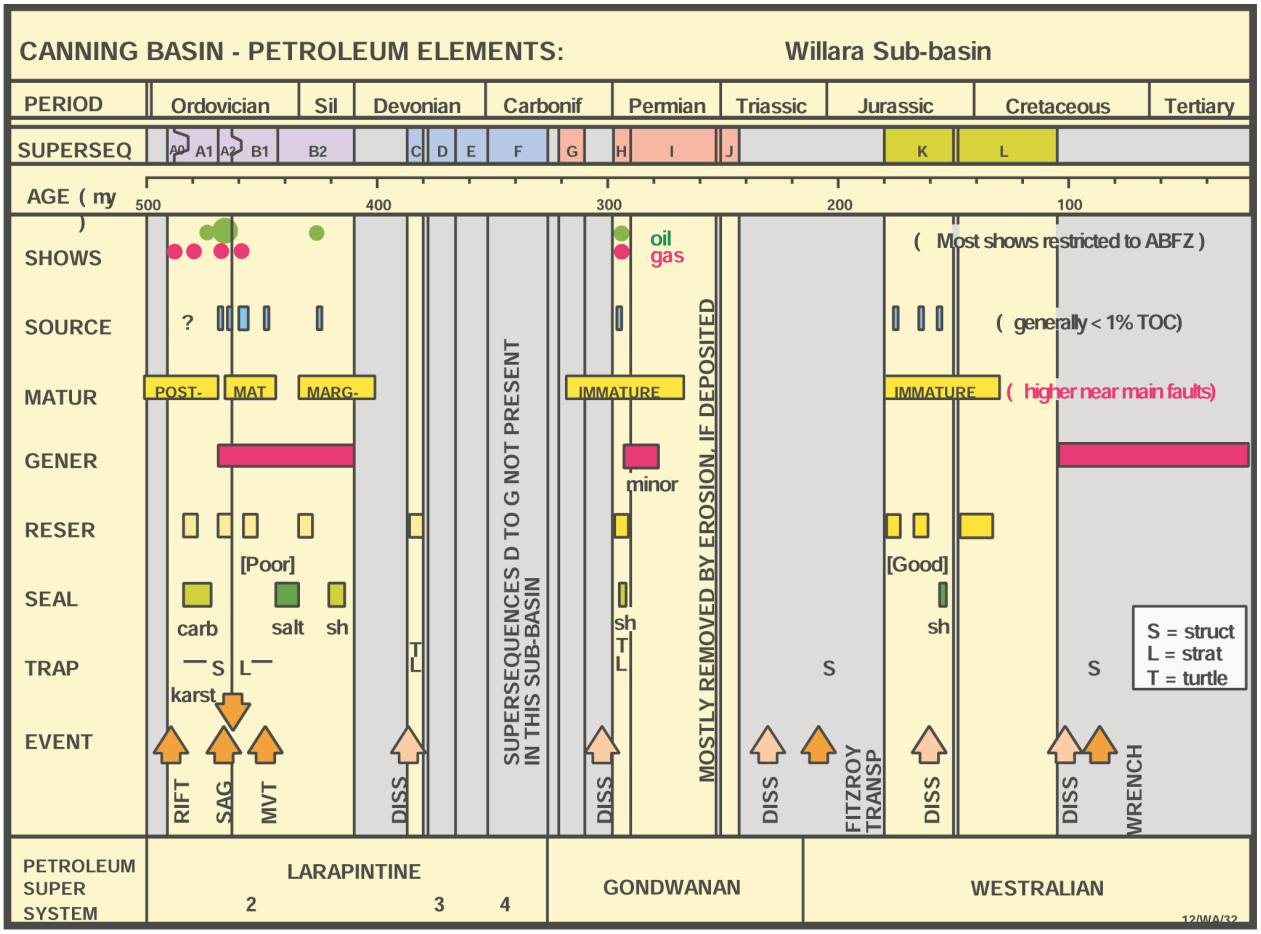


Figure II-19. Chart of events and key play elements of the Larapintine, Gondwanan and Westralian Petroleum systems, Willara Sub-basin (after Kennard *et al.,* 1994).

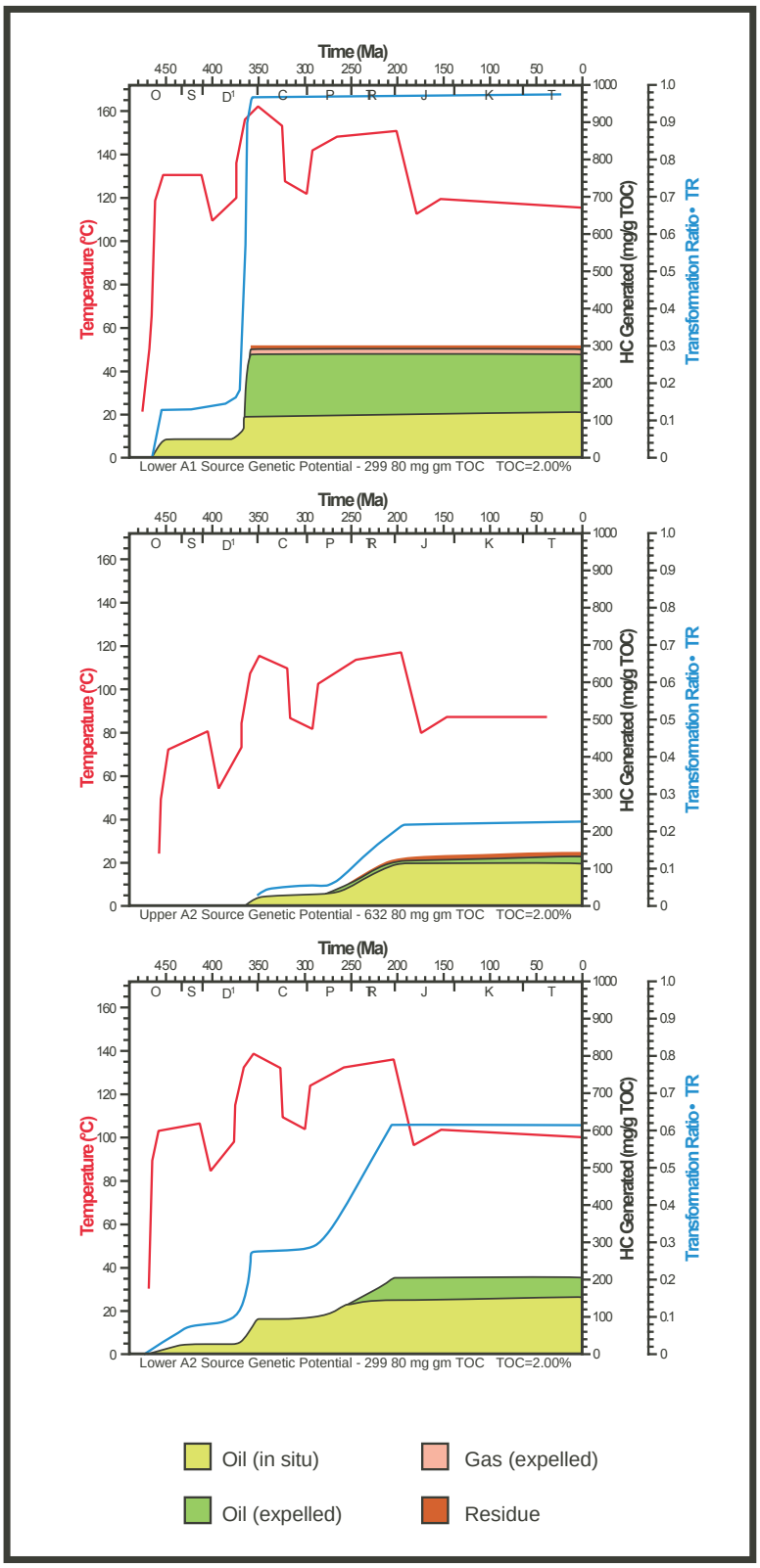


Figure II-20. Hydrocarbon Generation Plots of the Larapintine 2 petroleum source units calculated for the outer Dampier Terrace, Matches Springs-1 well (after Kennard, 1995).

BROWSE BASIN

Regional Geology

The northeast-trending Browse Basin underlies 240,000 km^2 of the North West Shelf to the west of the Kimberley Basin and is considered to extend to the continent-ocean boundary on the western side of the Scott Plateau (**Figure II-21).** It merges imperceptibly with the adjoining offshore Bonaparte and Canning Basins to the northeast and south, respectively (Elliott, 1990; Maung *et al*., 1994; Symonds *et al*., 1994). The major structural elements are the Caswell or Central Browse, the Seringapatam and the Barcoo Sub-basins. The Londonderry High, Yampi Shelf and Leveque Shelf form the eastern flank of the basin with a major south-west to northeast-trending Basin Margin Fault Zone (BMFZ) marking the outer boundary with the Yampi Shelf. There are several significant sub-parallel northeast-trending structural highs. The giant gas and condensate discovery at Scott Reef is located on one of these highs, the Scott Reef Trend. The primary basin architecture is largely the result of northeast-southwest Late Devonian to Early Carboniferous intracratonic, upper crustal extension and a north-south to northwest-southeast orientated full-lithosphere extension of mid-Carboniferous to Early Permian age (Symonds *et al.,* 1994). Later deformation events occurred in the Late Permian-Early Triassic (sometimes called Bedout Movement), the Middle to Late Triassic (Fitzroy Movement) and the Middle-Late Jurassic(Callovian-Oxfordian: Argo break-up). These were followed by a number of reactivation events in the Cretaceous to Tertiary. The Fitzroy Movement, a transpressional reactivation, led to inversion along the Scott Reef Trend and other major fault systems and resulted in Early-Middle Jurassic depocentres forming throughout the Caswell Sub-basin. Where drilled on the flanks, these rocks are fluvio-deltaic to marginal marine in nature unlike the deeper basinal shales of the Dampier and Vulcan Sub-basins.

Stratigraphy and Petroleum Systems

There is no formal stratigraphic nomenclature for the basin. **Figure II-22** summarises the Browse Basin petroleum systems as defined by the time-slice approach developed by AGSO's Australian Petroleum Systems project team. **Figure II-23** shows potential mature source intervals in the Permian, Jurassic and Cretaceous. From the viewpoint of known oil occurrence, the Browse Basin 'appears' to be the poor cousin of the Dampier Sub-basin to the south. This idea gained some credence because, in the Late Jurassic, the Browse Basin lacked the topographic contrasts (i.e. potential source rock depocentres) found in areas like the fault-bounded Swan Graben or Lewis Trough which operate as the discrete kitchens for Westralian source rocks within the Bonaparte and Carnarvon Basins. Outer basin highs partially embayed the shelf setting in the Browse Basin creating lower energy environments and generally shallower waters. **Figure II-24** shows the Late Jurassic paleogeography of the North West Shelf. It illustrates the contrast between the Dampier Sub-basin with deep water environments embayed behind the Rankin Platform (RP), and the Browse Basin with relatively shallow waters. This resulted in generally thinner Oxfordian to Kimmeridgian source units over much of the basin in comparison to the Dampier, Barrow and Vulcan Sub-basins. However, recent deep crustal seismic data suggest that there may still be some isolated and untested pods of thicker Jurassic sediments proximal to the Scott Reef Trend (Symonds *et al*., 1994).

The fundamental difference in behaviour of the Browse Basin may be the result of its sediments being deposited on a less rigid (i.e., sagging rather than faulted) lower plate segment of continental margin. Hence, it appears to be a Cretaceous rather than Jurassic depocentre with the implication that there is potential for mature Cretaceous source rocks to augment the (perhaps) less effective Late Jurassic sequence. **Figure II-25** maps the play area for the Late Cretaceous sandstone reservoir sequence in the Browse Basin.

Regional analogies would suggest that the Browse Basin may have some potential for hydrocarbons located within the underlying Gondwanan Supersystem (Bradshaw *et al*., 1994). **Figure II-26** maps the play area for a Permian/Triassic sequence analogous to the Tern and Petrel gas discoveries in the Petrel Sub-basin and the Dongara Saddle Oil Fields of the Perth Basin. However, the elements of the system in the Browse Basin are not as favourably combined as they are in these other examples.

Figure II-27 maps the play area for the operating Late Triassic-Early Jurassic petroleum system of the North Scott Reef-1 and Scott Reef-1 and 2 discoveries. The elements of this system are listed in **Table II-2**. **Figure II-28** shows relative timing for the Browse petroleum system elements.

Petroleum System Elements for the Late Triassic / Early Jurassic Time Slices Tr5-6, J1-2

Successful play: gas and condensate discoveries at Scott Reef-l, North Scott Reef-l and Keeling-l.

Potential Reservoirs: i) Carbonate facies in Upper Triassic - shallow platform, reef facies.

Proven Reservoirs: i) Sands in late Triassic and early Jurassic, beach to lluvio deltaic facies, 18-23% porosity in Keeling-1.

Potential Seals: i) intraformational seals, e.g. top of Tr6 in Barcoo l.

Proven Seals: i) Conformable top seal in J2 as at North Scott Reef-l sealing gas and condensate zone in Jl. J2 is usually a finer grained facies related to sea level rise -but a patchy seal.
ii) Unconformable top seal in later Jurassic (J6 over gas zone in Try & K in Scott Reef-1)
iii) Unconformable top seal in Cretaceous (K~ over gas zone in TrS16 in Keeling-l)

Potential Sources: i) possible migration up faults from underlying Permian and Lower Triassic, though source quality and maturation risks.
ii) Local source potential poor in high energy shallow marine to fluvial facies, some potential in lower energy deltaic facies

ProbableSource: i) migration from Upper Jurassic sources located down dip?.

Traps: Stratigraphic (reef, sand bar) and/or structural traps formed during Jurassic or Cretaceous structural events.

Intersections: Ashmore Reef-1, Mount Ashmore-l, Keeling-l, Brecknock-l, Scott Reef-l, North Scott Reef-1, Woodbine-1, Barcoo-1, Lynher-1, Lombardina-l, Buffon-1.

Shows: Gas and condensate zones at Scott Reef-1, North Scott Reef-1, Keeling-1.
Gas & oil indications at Mount Ashmore-1, Buffon-l, Lombardina-l, Lynher-l.
Gas indications at Woodbine-l, Brecknock-1.

Distribution: Depth to the top Triassic in the centre of basin restricts the play area to the basin margins. The play has been successful along the Scott Reef Trend and in the north-east corner at Keeling-1. There is also a limited potential play area along the inner basin margin if suirable structures exist (Fig. 18).

Risks: Top seal, source quality.

Table II-2. Elements of the Proven Late Triassic-Jurassic Petroleum System of the Browse Basin (after Bradshaw *et al*., 1994).

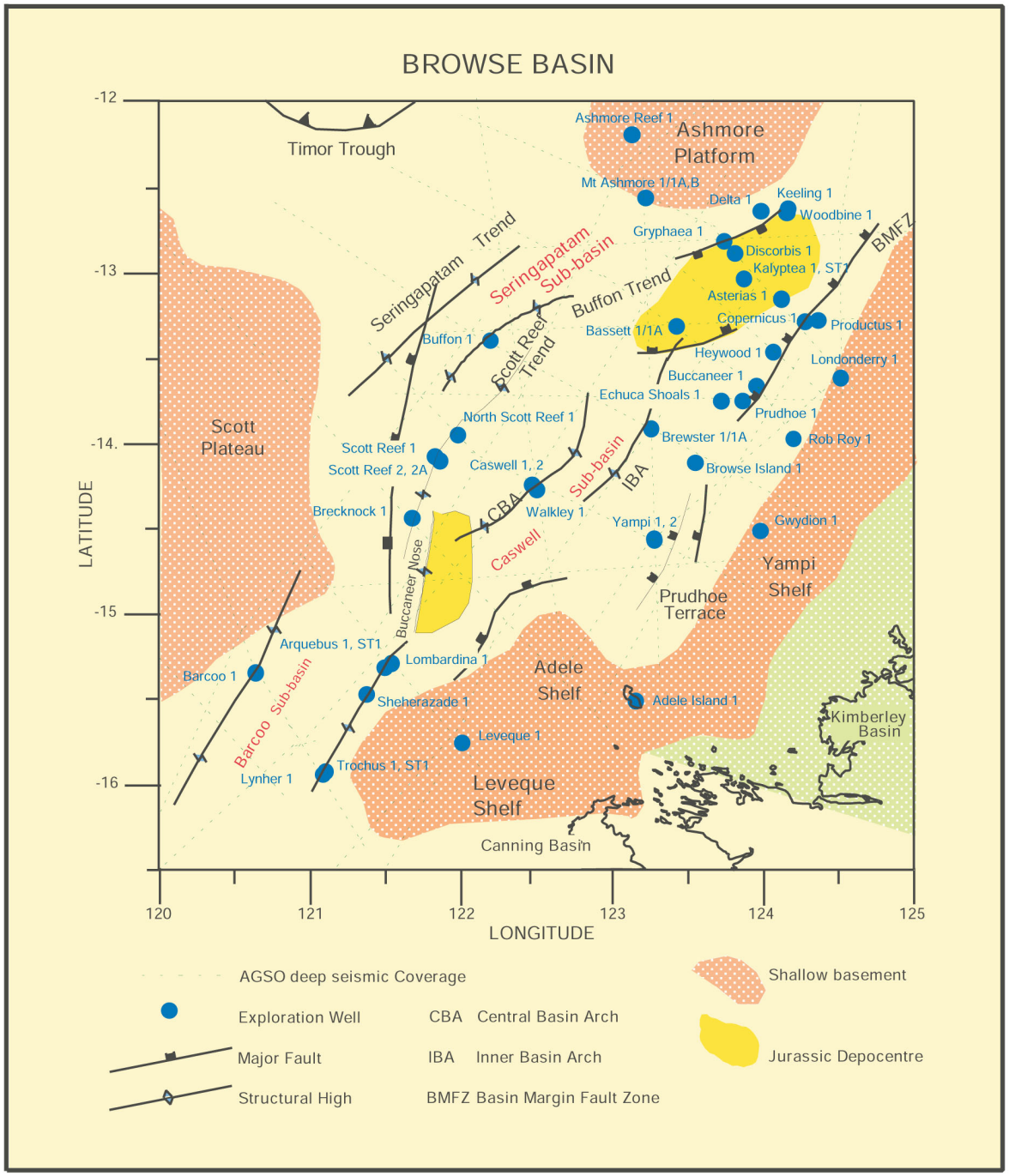


Figure II-21. Map of the Structural Elements of the Browse Basin (after Symonds *et al*., 1994).

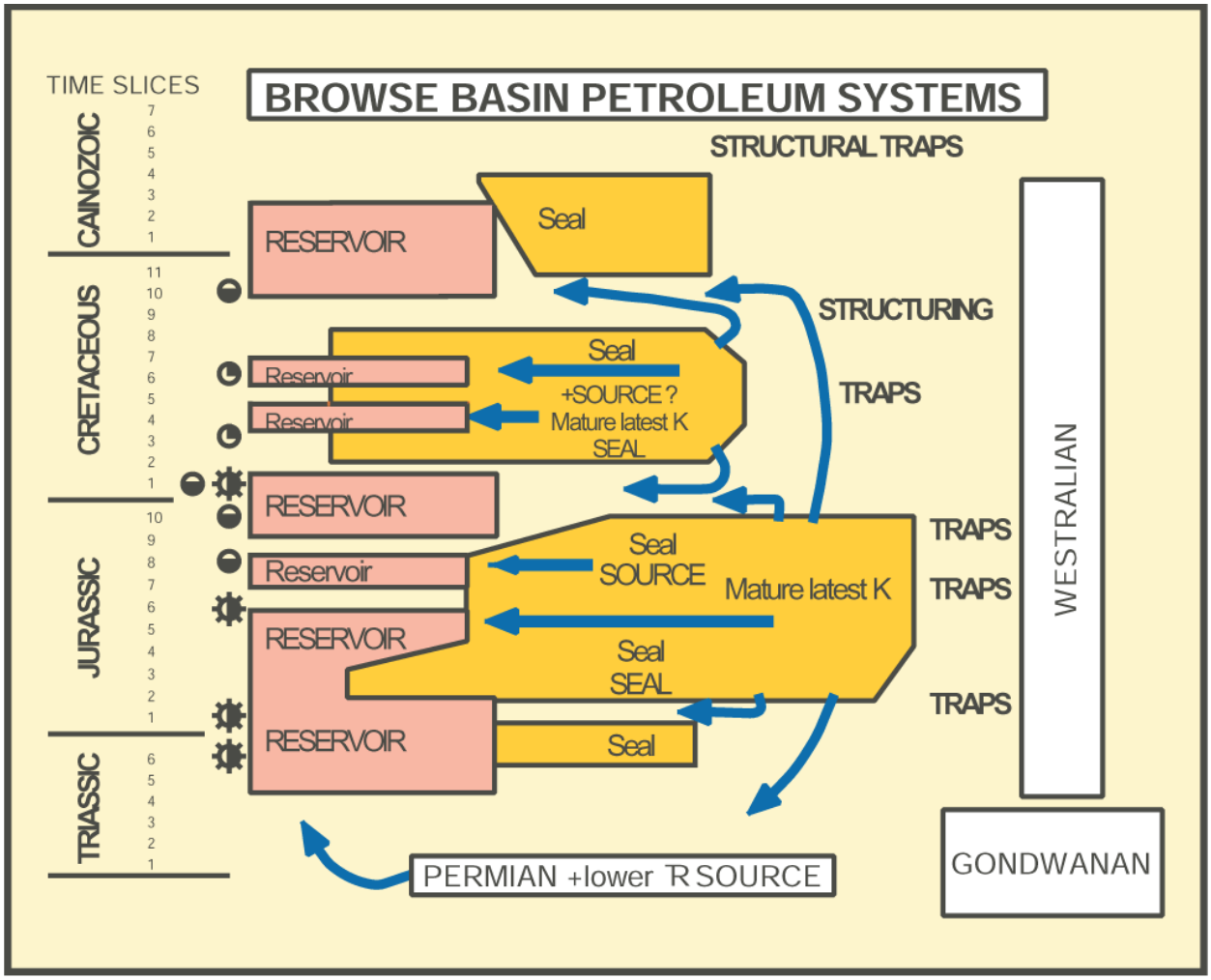


Figure II-22. browse basin Petroleum systems 9after Bradshaw *et al.,* 1994).

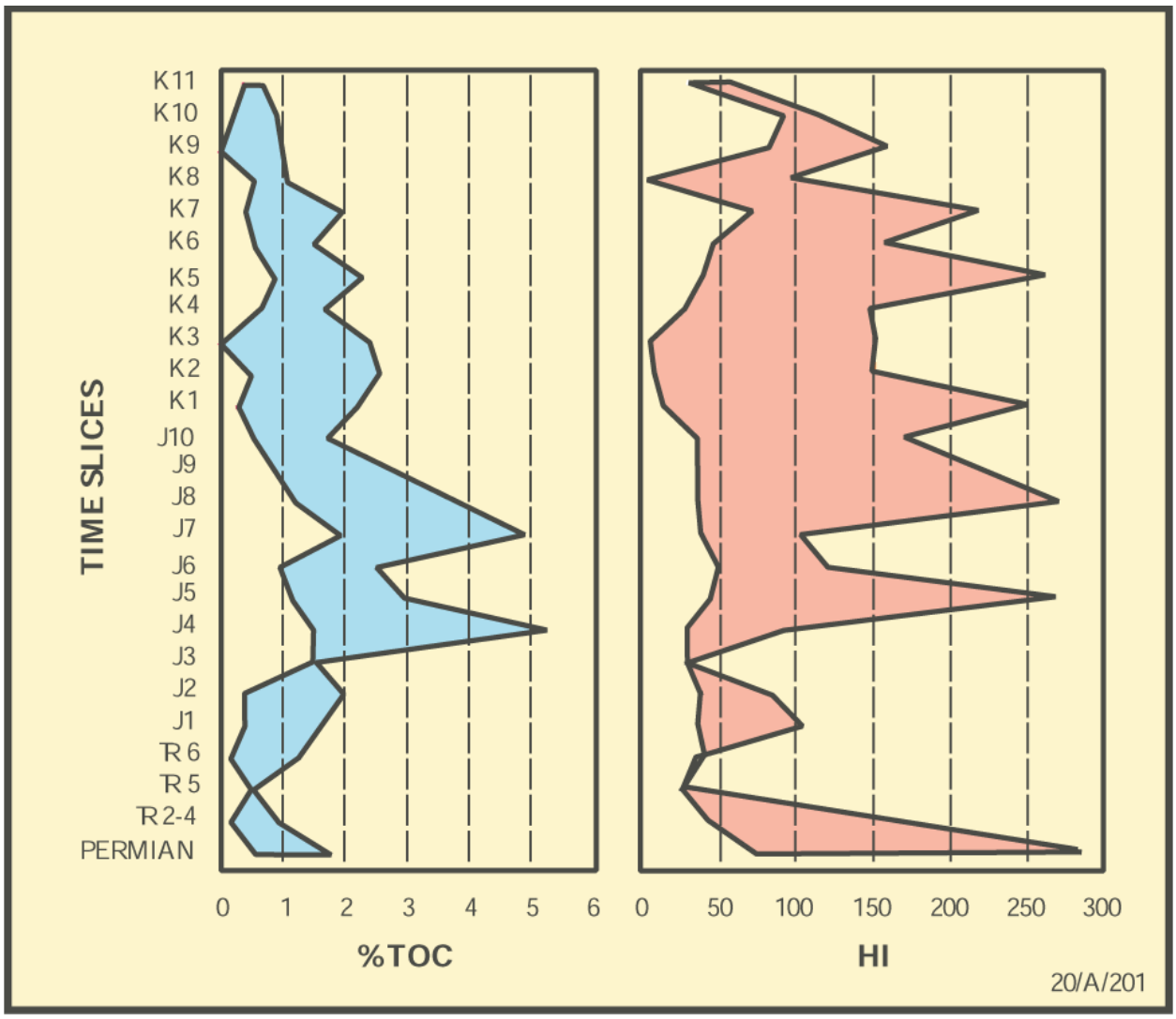


Figure II-23. Source Rock Quality Data for samples from the Browse Basin time-slices (after Bradshaw *et al*., 1994). Note: data set is relatively small and is from AGSO 'Orgchem' database using APS time-slices.

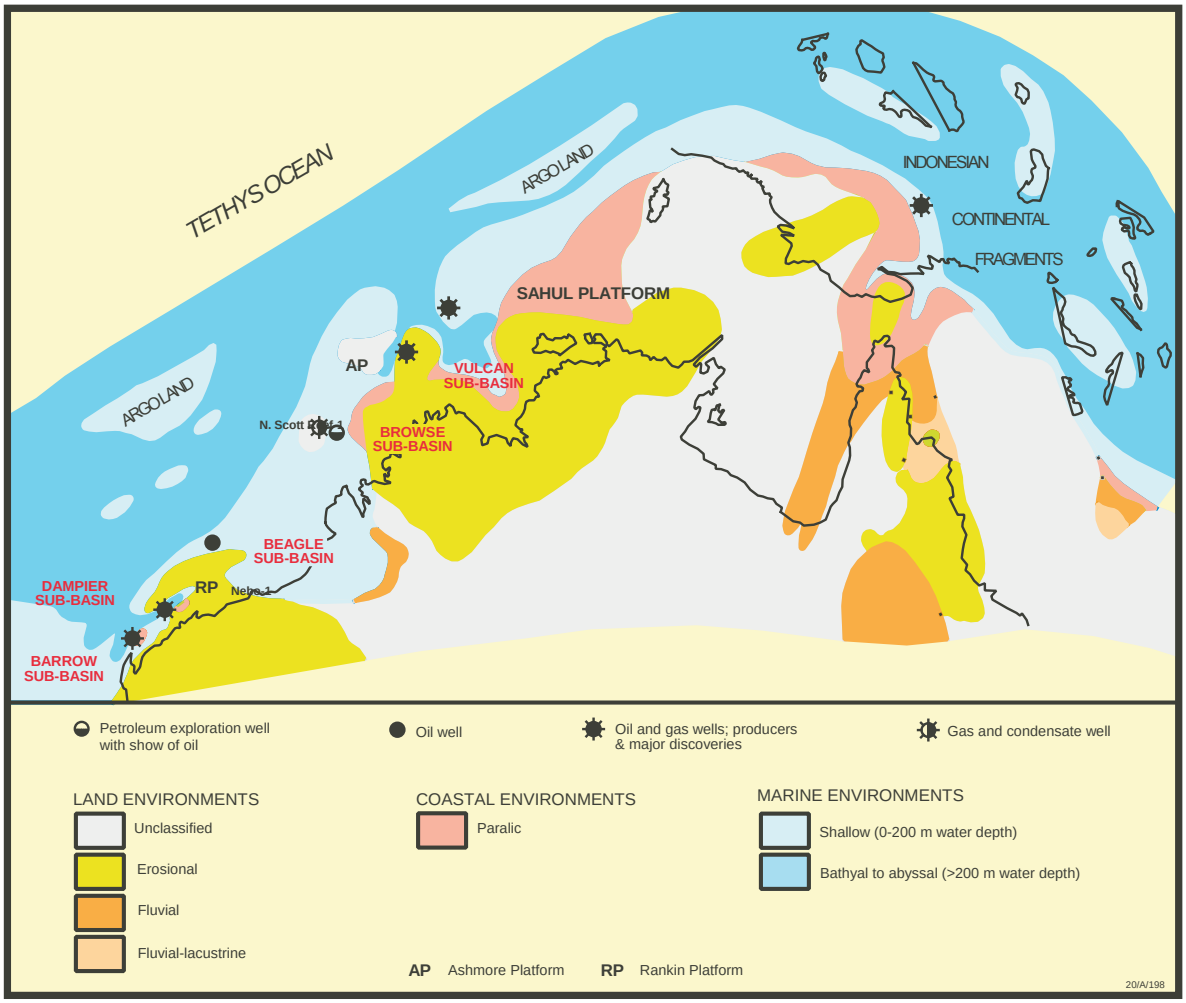


Figure II-24. Paleogeographic Map of the North West Shelf in the Late Jurassic (after Bradshaw *et al*., 1994). The figure shows, from south to north, generalised locations of the producing fields of the Barrow, Dampier and Vulcan Sub-basins and the recent discoveries on the Sahul Platform. All are located within or adjacent to Late Jurassic deep water depocentres. Also indicated are the locations of the Nebo-1 (Beagle Sub-basin) and North Scott Reef-1 and Caswell-2 discoveries (Browse Basin) and their relationship to what were shallower water facies at this time.

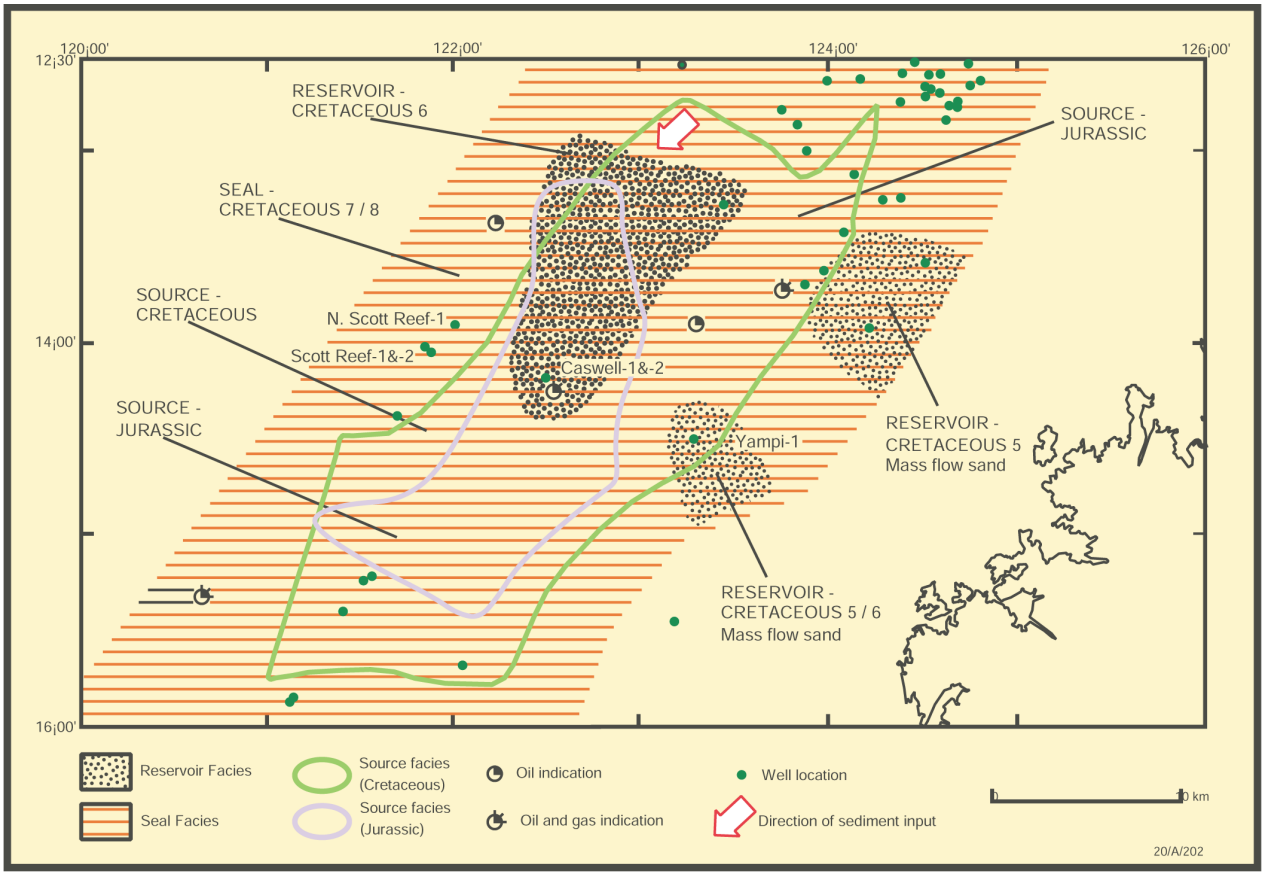


Figure II-25. Play area for a Cretaceous Petroleum system in the Browse basin (after Bradshaw *et al.,* 1994).

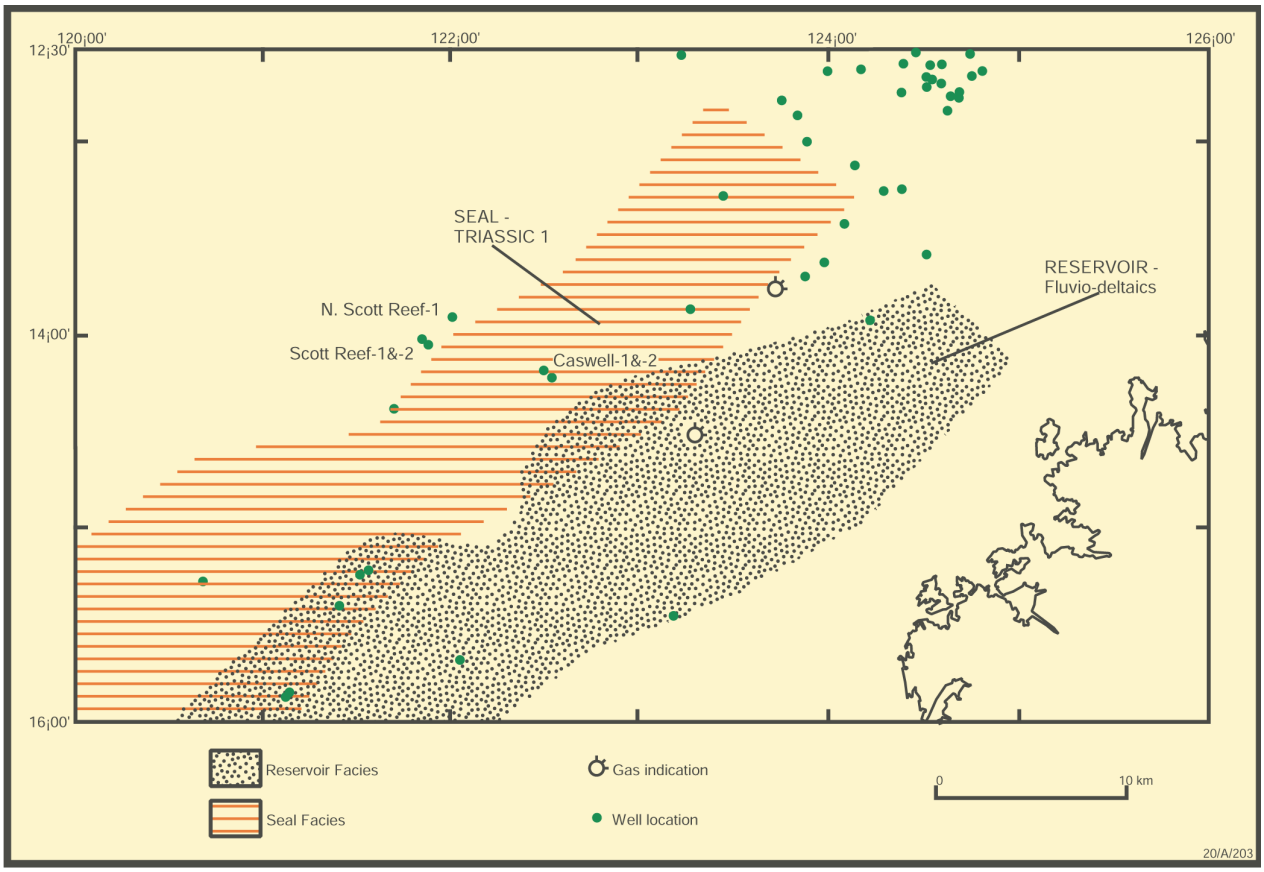


Figure II-26. Play area for Permian-Basal Trissic Petroleum system in the Browse Basin (after Bradshaw *et al.,* 1994).

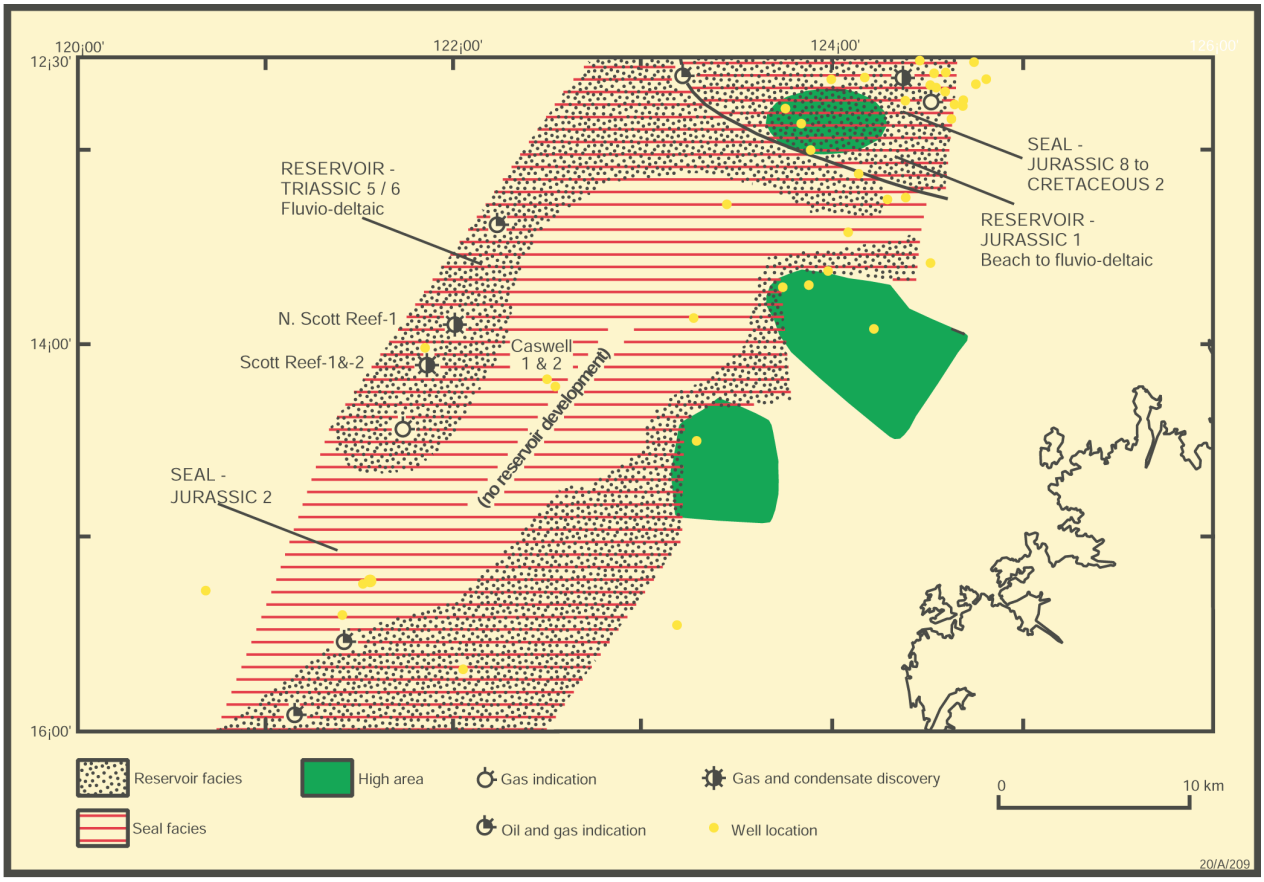


Figure II-27. Play area for the Late Triassic-early Jurassic sequence of the Browse Basin (after Bradshaw *al.,*

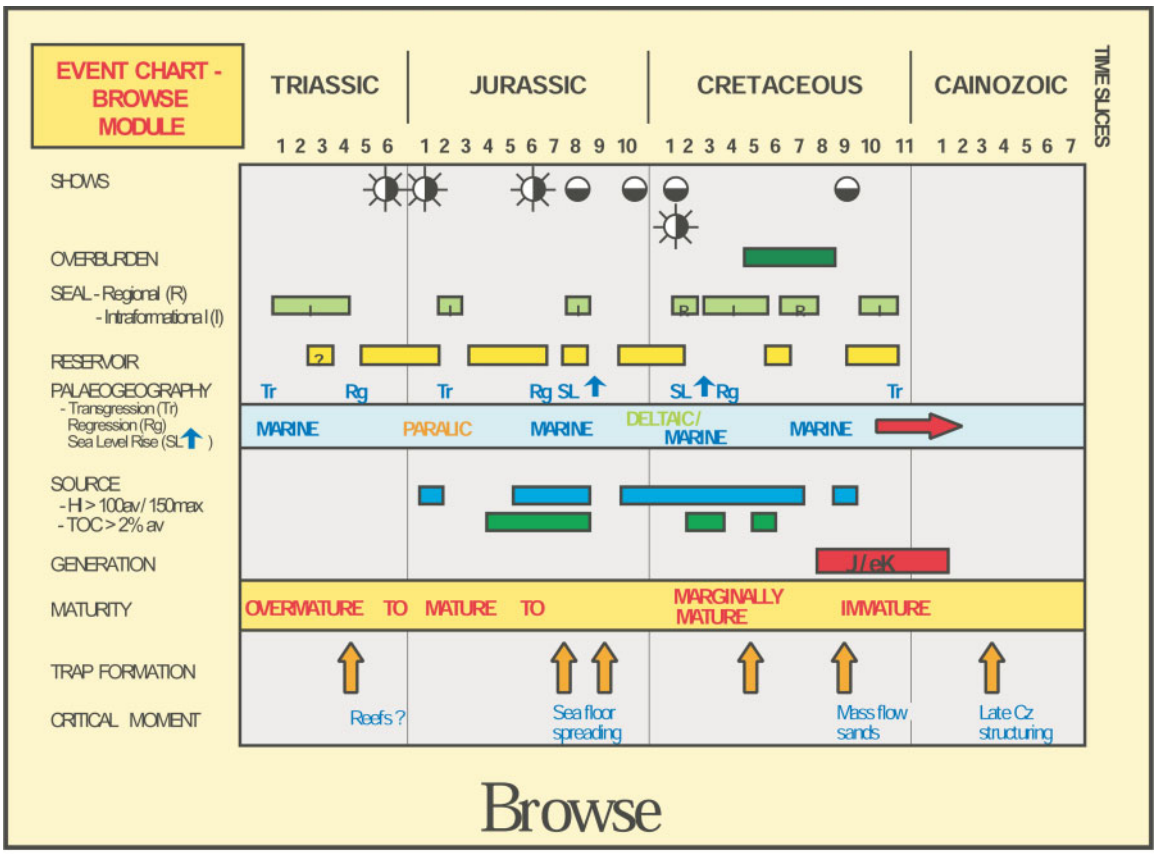


Figure II-28. Event chart for the Browse Basin (after Bradshaw *et al.,* 1994)

CARNARVON BASIN

Regional Geology

As with other major basins of the North West Shelf, the Carnarvon Basin comprises stacked basins of early to middle Paleozoic age overlain by late Paleozoic to Cainozoic elements of the Westralian Superbasin. The older section occupies the north-south trending, mainly onshore southern Carnarvon Basin, which developed initially as a northwards-opening rift basin in the Late Ordovician-Silurian, evolved into a broad downwarp, and has been essentially inactive since the latest Permian (Hocking *et al*., 1994).

The northern edge of the southern Carnarvon Basin is truncated by the northeast-trending Northern Carnarvon Basin, a component of the Westralian Superbasin. From southeast to northwest (**Figure II-29**), the northern Carnarvon Basin comprises an inner shelfal area flanked by a northwestwards-deepening terrace, an inner complex of mainly Jurassic-Cretaceous depocentres (Exmouth, Barrow, Dampier and Beagle Sub-basins) beneath the continental shelf and upper slope, and a major platform of thick, flat-lying sediments (Exmouth Plateau), the inner flank of which is relatively elevated to form the Rankin Platform and Alpha Arch. Oceanwards of the Exmouth Plateau is the Late Jurassic oceanic crust of the Argo Abyssal Plain to the north and the Cretaceous oceanic crust of the Gascoyne and Cuvier Abyssal Plains to the northwest and southwest, respectively.

The regional geology of the northern Carnarvon Basin has most recently been summarised by Stagg and Colwell (1994), on the basis of an interpretation of AGSO deep seismic data and earlier studies. The following summary of their work is illustrated in **Figures II-30** and **II-31**.

Permian rocks have only been drilled beneath the nearshore flank of the basin. These rocks are typically contained within landwards-soling fault blocks that exhibit moderate extension beneath the Enderby Terrace. They constitute the first section that can be ascribed to the Westralian Superbasin, and thus may extend back to the Carboniferous. Oceanwards of the inboard depocentres, no rocks older than Middle Triassic have been drilled, and the presence of a Permo-Carboniferous section is only inferred on the basis of seismic character. Over most of the northern Carnarvon basin, the Permo-Carboniferous is a flat-lying sequence that shows little evidence of extension, and is interpreted to be a sag-phase section, possibly 3-5 km thick, deposited following the extensional phase that initiated the Westralian Superbasin.

The distribution and geometry of the Triassic section is interpreted to be similar to the underlying late Paleozoic section. This section, which comprises the transgressive Locker Shale and the thick, fluvio-deltaic Mungaroo Formation, is ~5-6 km thick beneath most of the basin, thinning to a feather edge at the southeasten margin. Faulting at the top of the Triassic section is the most prominent structuring episode in the basin, and is particularly well-developed on the Rankin Platform and Exmouth Plateau. The Mungaroo

Formation is the principal reservoir for the giant gas-condensate fields on the Rankin Platform.

The geometry and distribution of the Jurassic section varies markedly throughout the basin. In the Exmouth, Barrow and Dampier Sub-basins, rapid subsidence resulted in deposition of the thick, restricted marine shales of the Dingo Claystone that, in the Early to Middle Jurassic, attained a thickness of 3-4 km. Subsidence was contemporaneous with deposition, leading to pronounced thinning of the sediment package across the trough margins. Continued high sediment supply in the Middle to Late Jurassic eventually filled the troughs and spilled over the margins. On the Exmouth Plateau, Jurassic sedimentation was much more restricted. Most wells on the plateau record only a thin veneer of Jurassic sediments above the high-standing Triassic fault blocks, while pockets of Jurassic sediments, up to a few hundred metres thick, are interpreted to be preserved in minor half-grabens in the Triassic surface (Spencer *et al*., 1995). In the Beagle Sub-basin and northern Exmouth Plateau, Jurassic sedimentation continued in the same style as in the Triassic. Here the geology is typically 'layer-cake' until the late Middle Jurassic (Callovian), at which time seafloor spreading commenced in the Argo Abyssal Plain, producing a strong erosional unconformity.

Early Cretaceous sedimentation is principally confined to the Barrow and Exmouth Sub-basins and the southern Exmouth Plateau, where a major deltaic complex (the Barrow Group) prograded northwards towards the open ocean formed by the spreading in the Argo Abyssal Plain. The Barrow Group is up to 2 km thick in the south, but thins markedly beyond the northerly limit of the prograding topsets. Deposition of the Barrow Group was abruptly terminated in the Early Cretaceous (Valanginian), with the initiation of a second episode of seafloor spreading in the Gascoyne and Cuvier Abyssal Plains and the removal of the major source of sediment supply to the south. The Barrow Group provides the reservoir rocks for many of the small to medium hydrocarbon discoveries in the Barrow Sub-basin.

Since the Valanginian break-up episode, sedimentation in the Late Cretaceous and Tertiary has taken place in an open marine environment with the water depth becoming progressively. This sedimentation has generally been concentrated in the near-shore depocentres, while the Exmouth Plateau is covered by a veneer of sediments that is rarely more than a few hundred metres thick. Initially, claystones and shales were deposited basin-wide (Muderong Shale and Gearle Siltstone). Extensive carbonate sedimentation commenced in the Turonian. During the remainder of the Cretaceous, sedimentation was fairly evenly split between open marine carbonates and claystones. Most of the Tertiary sequences in the northern Carnarvon Basin are the result of out- and up-building of the continental shelf during a series of transgressive/regressive sea level pulses, with the dominant sediment type being carbonate.

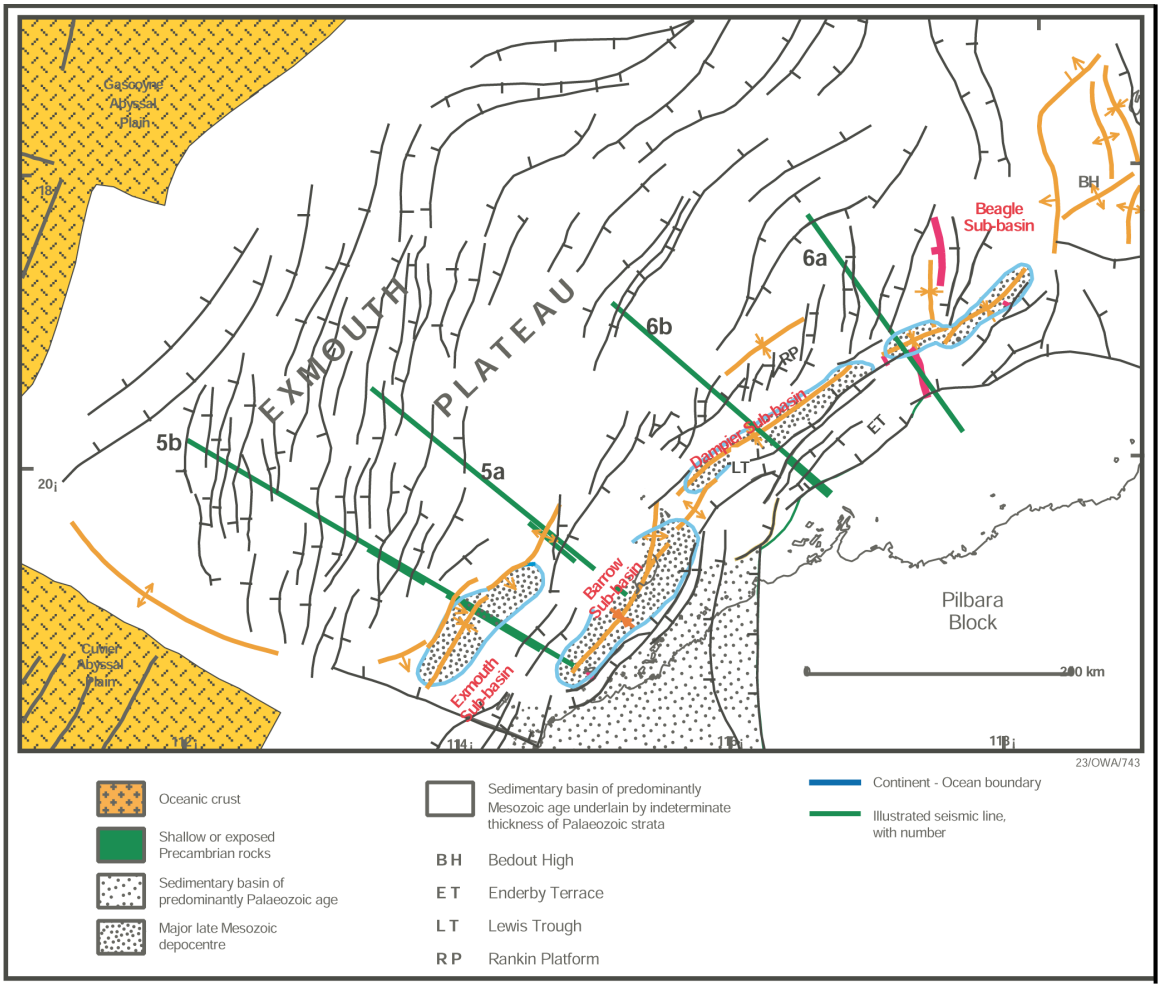


Figure II-29. Map of the subdivisions and structural Elements of the Northern Carnarvon Basin (after Stagg and Colwell, 1994).

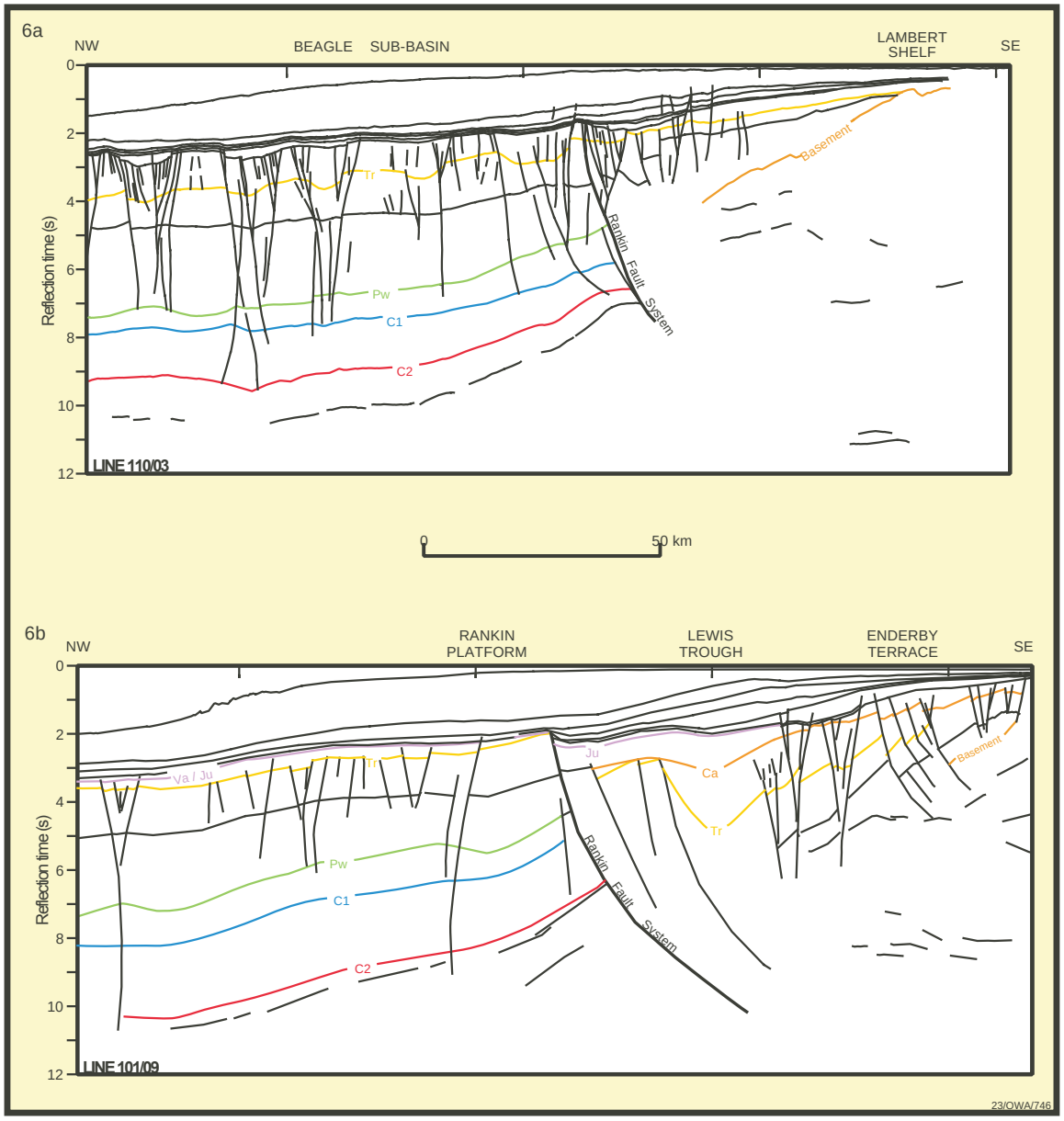


Figure II-30. Cross Sections Showing Elements of the Carnarvon Basin (6a) in a line from the Beagle Sub-basin to the inner Exmouth Plateau, and (6b) in a line across the Dampier Sub-basin (after Stagg and Colwell, 1994). Seismic horizons are identified in Figure II-29**.**

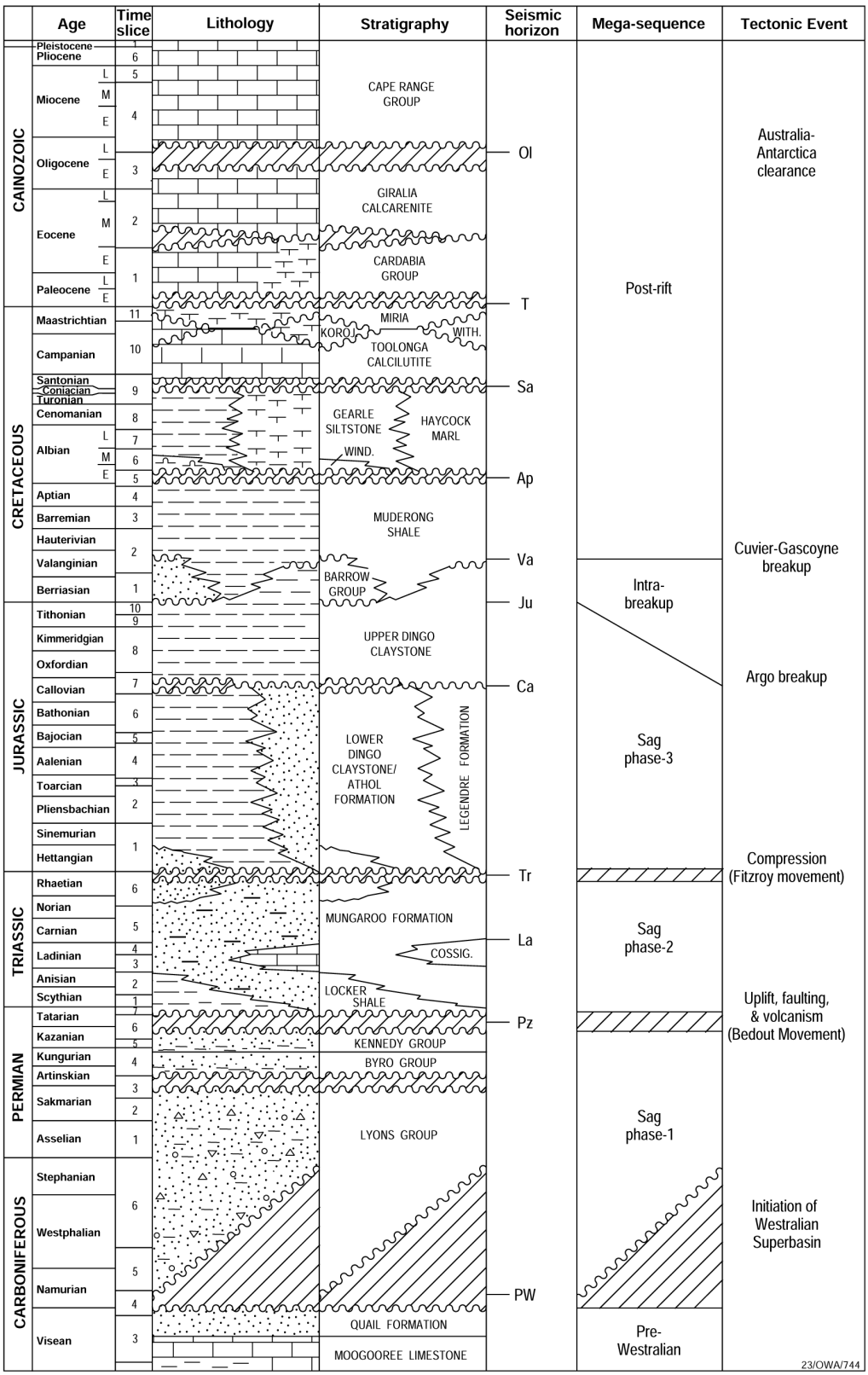


Figure II-31. Carboniferous to Cainozoic Stratigraphy of the Northern Carnarvon Basin (after Stagg and Colwell, 1994).

Stratigraphy and Petroleum Systems

Figure II-31 shows a generalised stratigraphy for the Late Paleozoic to Cainozoic of the Carnarvon Basin. As in the Bonaparte Basin, there is considerable production from accumulations residing in the Westralian Supersystem. The unambiguously identified oil source rocks occur within the Late Jurassic upper Dingo Claystone (Kopsen and McGann, 1985; Woodside Offshore Petroleum Pty. Ltd., 1988; Scott, 1992, 1994). As in the Bonaparte Basin, Middle Jurassic sediments such as the Legendre Formation have potential for oil and gas. The Early Triassic Locker Shale contains some localised oil-prone material in its basal parts, while through the overlying Mungaroo Formation there are significant concentrations of humic organic matter considered to be gas-prone. The prime Late Jurassic source rocks are considered to be deep water shales deposited in what were narrow restricted localities (**Figure II-24**). These are particularly expressed in the Lewis Trough, Dampier Sub-basin where the Wanaea and Cossack accumulations occur (e.g., Barber, 1994).

Similar Late Jurassic source rocks were deposited in less restricted marine environments in the Exmouth and Barrow Sub-basins. Deposition of the Early Cretaceous Barrow Delta had the impact of providing the major reservoir facies in the sub-basins as well as producing a different maturation history to that taking place in the Dampier Sub-basin. In the Barrow Sub-basin, Early Cretaceous as well as Jurassic source rocks may be mature with the main phase of generation taking place earlier than in the Dampier Sub-basin where it occurs in the Late Tertiary (**Figures II-32, II-33** and **II-34**).

Within the Westralian Supersystem of the Carnarvon Basin, prime oil reservoir facies are found in the deltaic and shallow marine Cretaceous sands of the Winning (Mardie, Birdrong and Windalia Sandstones) and Barrow (Flacourt and Malouet Formations and Flag Sandstone) Groups and in Late Jurassic turbidite sands in the Dampier Sub-basin. Gas on the Rankin Trend and elsewhere is reservoired in the Triassic Mungaroo Formation. The Muderong Shale forms a regional seal for the system.

There has been limited exploration success in the Beagle Sub-basin (Blevin *et al*., 1993, 1994) where the Nebo-1 oil stands out as an exception (**Figures II-35** and **II-36**). Maturity and source thickness and quality considerations preclude a Dingo Claystone-like Late Jurassic source. This oil is reservoired in the mainly Middle Jurassic (Callovian) Calypso Formation (Osborne, 1994) and may have been sourced from an oil-prone facies within the Early-Middle Jurassic Legendre Formation. This petroleum system is dependent on deep faults to provide conduits from the mature section to the younger reservoirs.

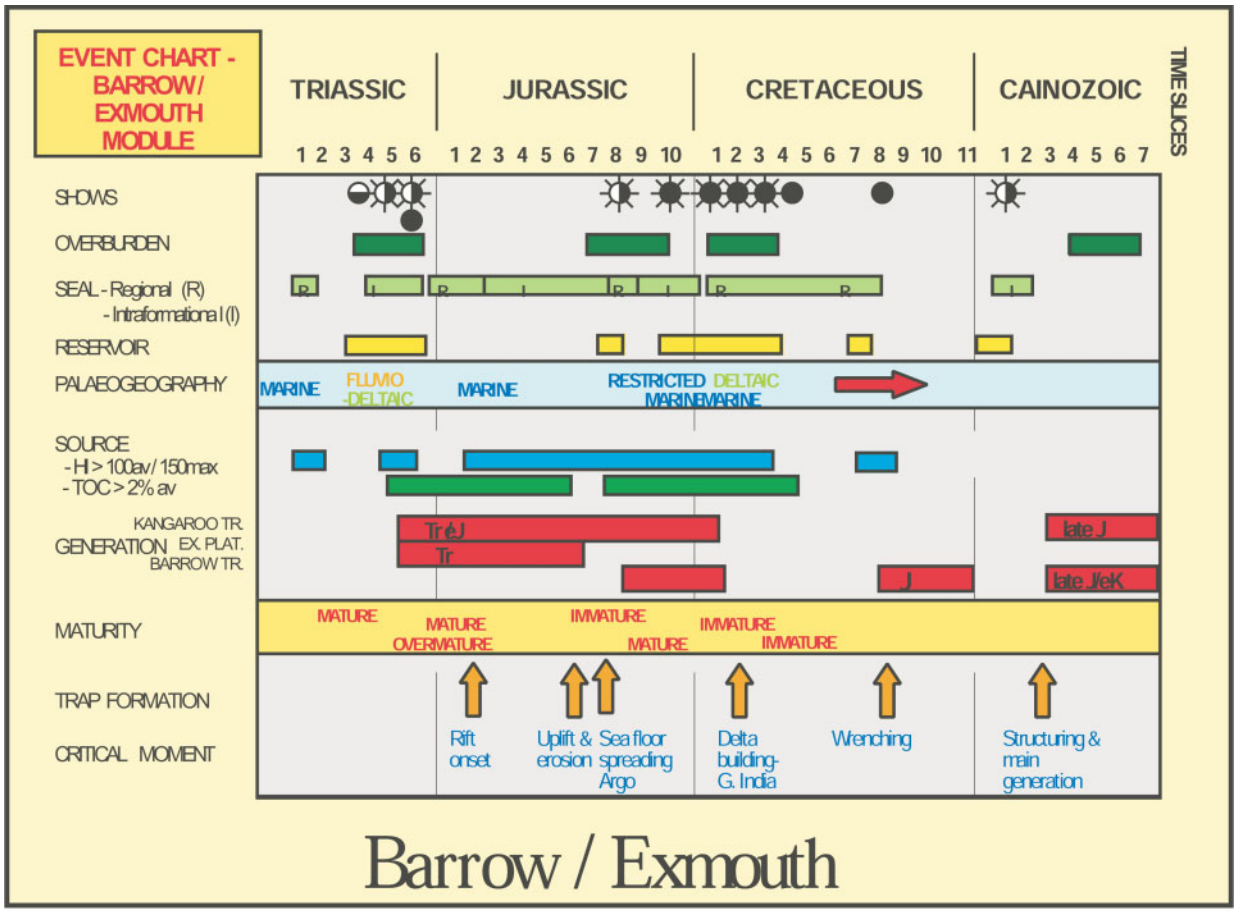


Figure II-32. AGSO-APIRA Australian Petroleum systems (APS) event chart for the timing of respective elements of the Barrow-Exmouth region (courtesy of J. Bradshaw).

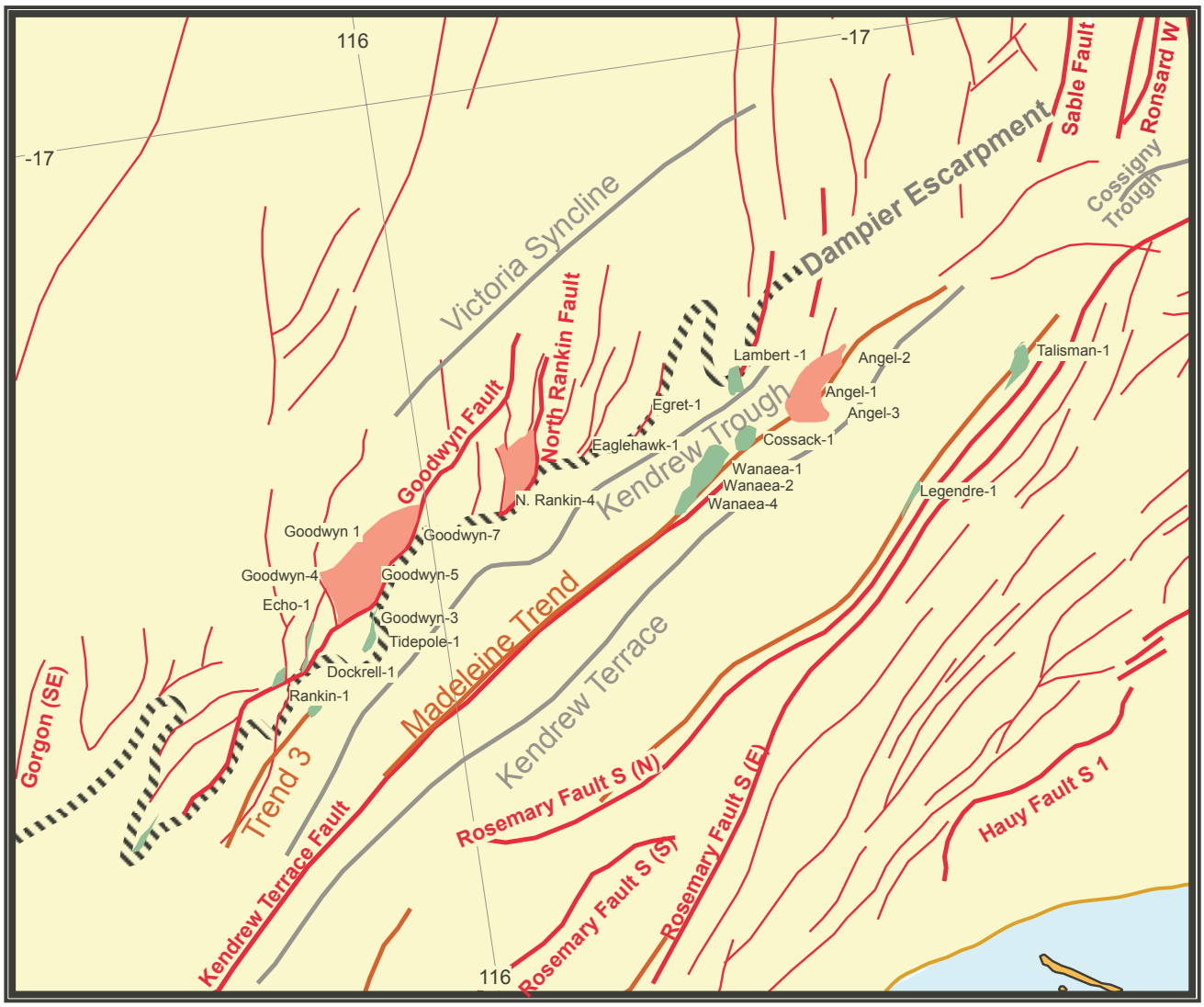


Figure II-33. Map Showing Structural Elements of the Dampier Sub-Basin and Rankin Trend (after Hill, 1994 and others).

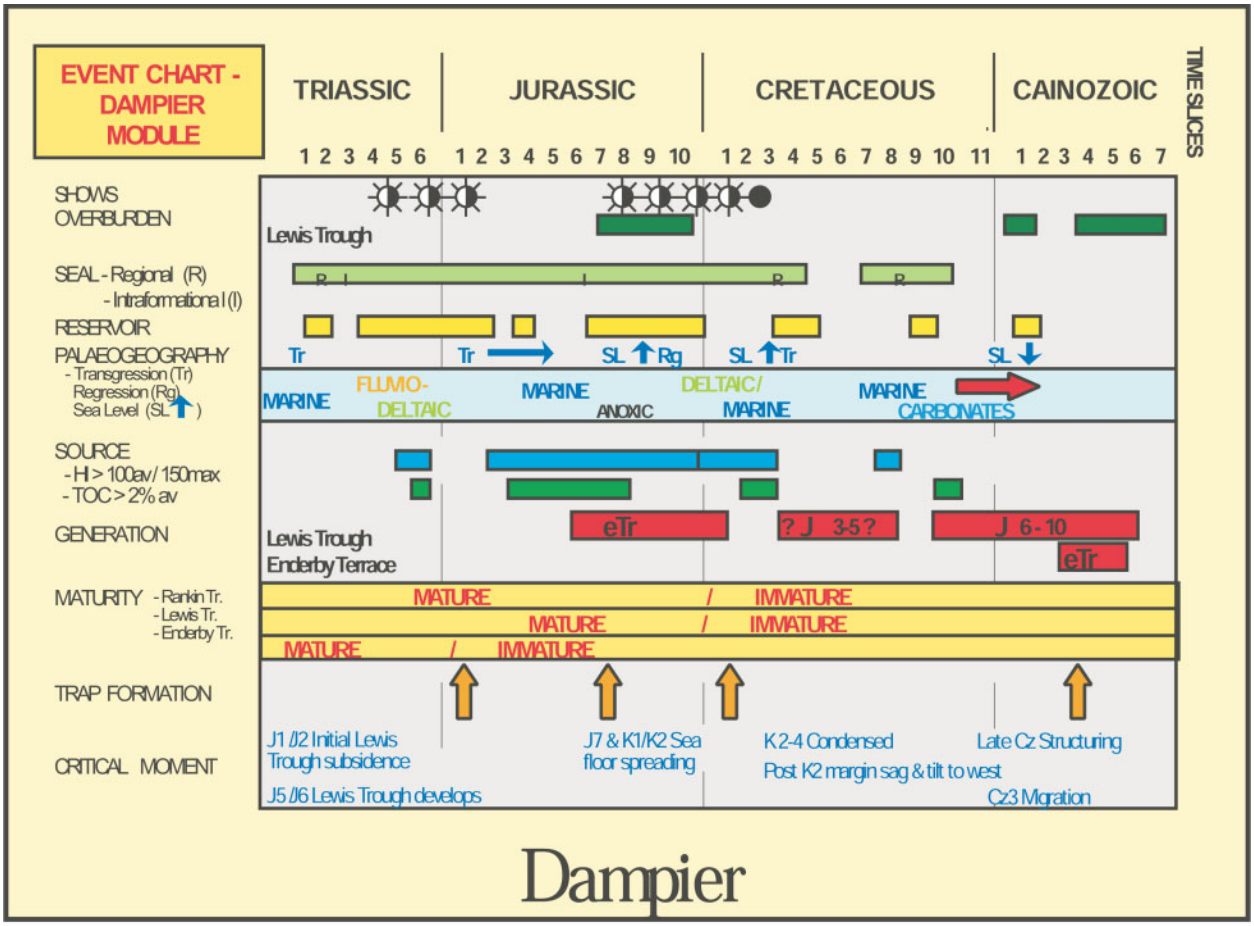


Figure II-34. AGSO-APIRA Australian Petroleum systems (APS) event chart for the timing of respective elements of the Dampier Sub-basin systems (courtesy of J. Bradshaw).

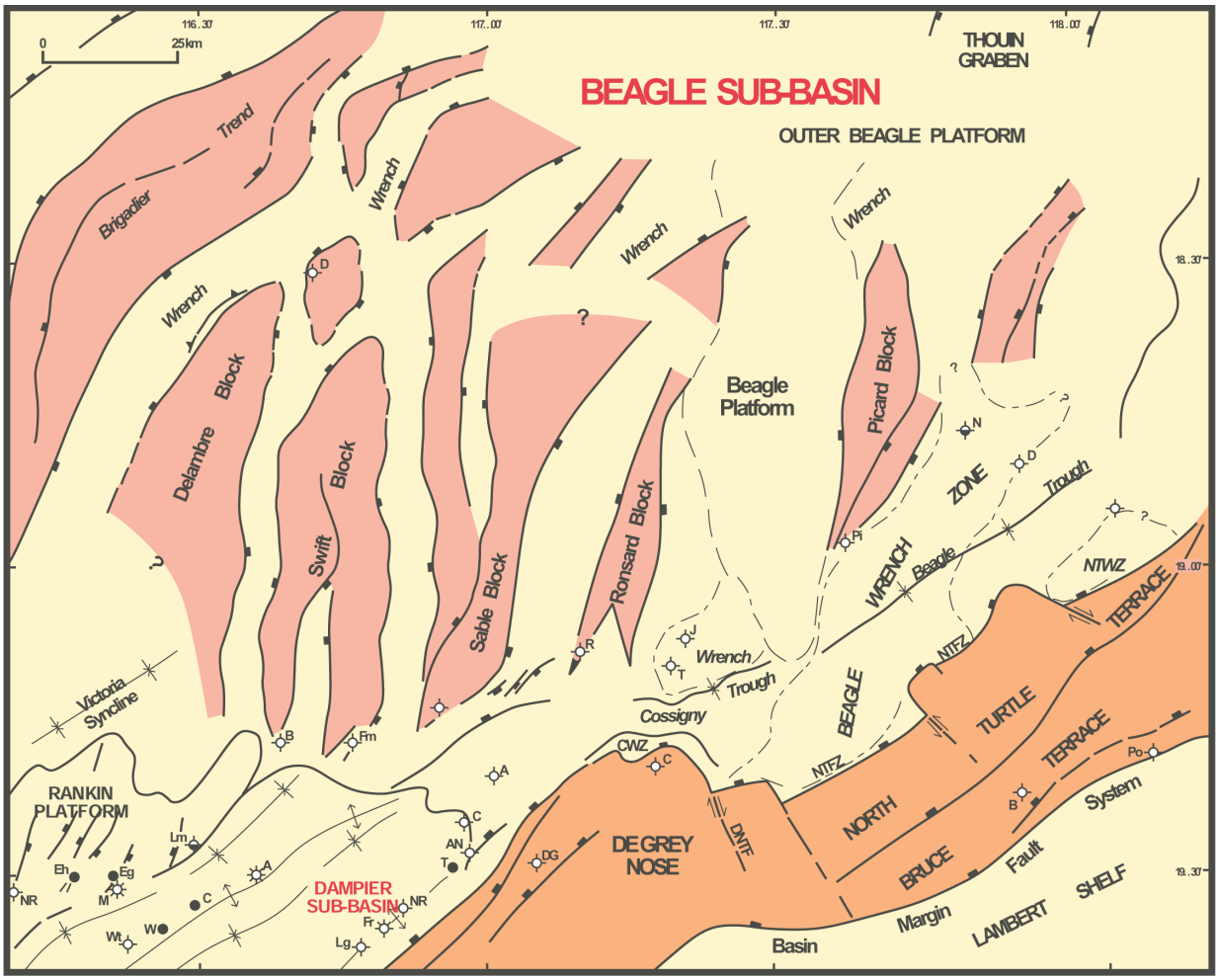


Figure II-35. Map showing structural elements of the Beagle Sub-basin.

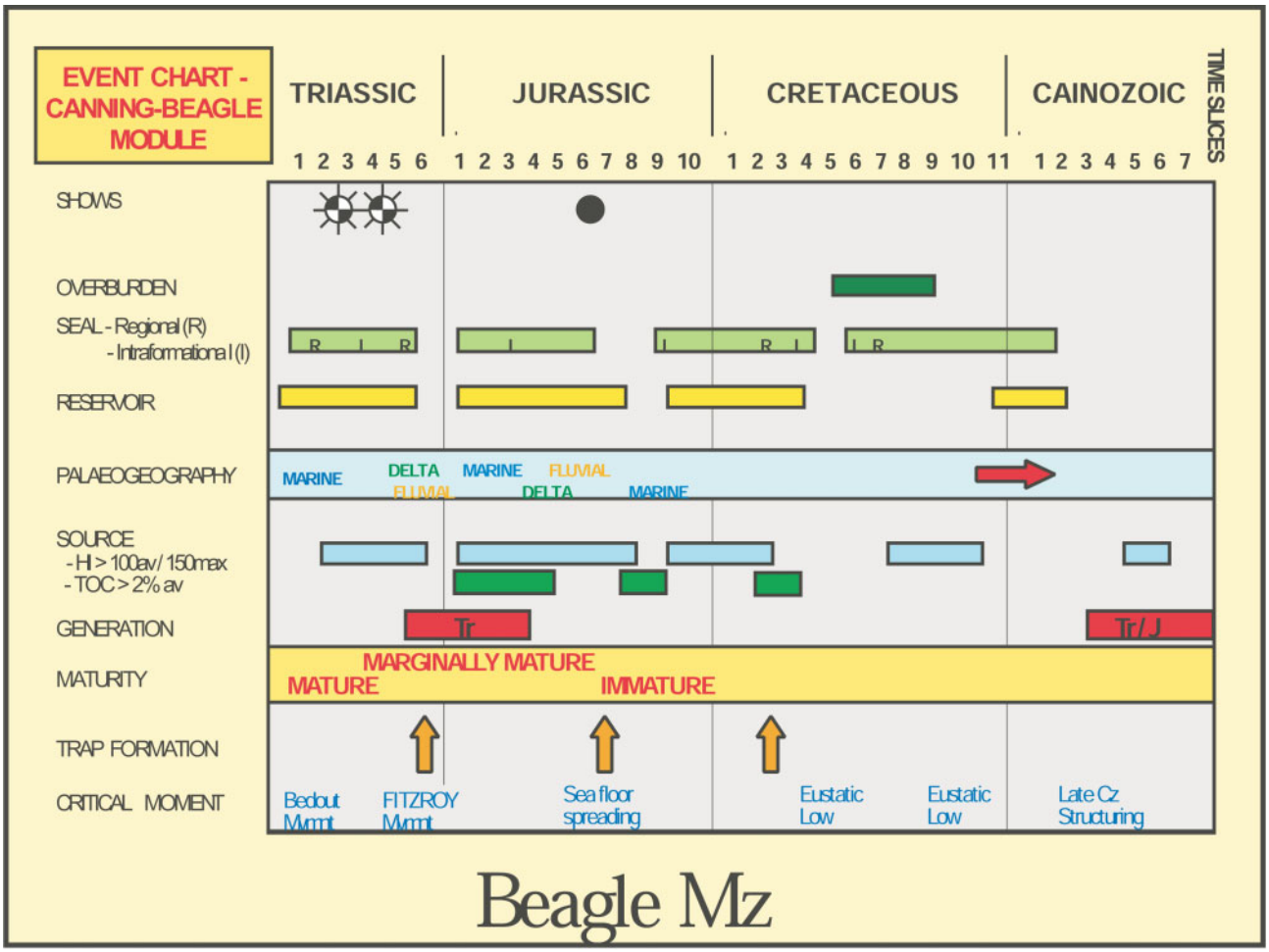


Figure II-36. AGSO-APIRA Australian Petroleum systems (APS) event chart for the timing of respective elements of the Beagle Sub-basin systems (courtesy of J. Bradshaw).

In the Carnarvon Basin, and especially in the Barrow Sub-basin, there is risk associated with drilling sub-commercial gas versus commercial oil accumulations; and gas, oil and mixed accumulations occur in close proximity. Examples include the South Pepper and North Herald Fields where there is oil, compared to Pepper-1 and Elder-1 where there is both gas and condensate. The reasons for this dramatic variation in hydrocarbon phase have been ascribed variously to source quality, source maturity, trap integrity and different migration pathways. Development of sound, remote sensing predictive methods to reduce this risk depends on gaining a more thorough understanding of the relationships between hydrocarbon charge, preservation history and the possibility of remigration and entrapment, as suggested for the Timor Sea (O'Brien and Woods, 1995). The oil family correlations presented in this report also play an important role in attempting to solve this problem.

PERTH BASIN

Regional Geology

The Perth Basin is a deep and linear trough extending over 1000 km from Geraldton in the north to the south coast of Western Australia (**Figure II-37**). The Permian to Early Cretaceous sedimentary fill was deposited in a continental rift and overlain by an Early Cretaceous (Valanginian) to Quaternary succession laid down in a marginal sag basin. The tectonic development and the style of sedimentation in this area contrasts markedly to that of the North West Shelf region to the north.

The basin is bounded to the east by the north-south trending Darling Fault and this has been downthrown on its western side by as much as 15 km since the Early Paleozoic (Hall, 1989; Marshall *et al*., 1989 and references therein). The main depocentre is the Dandaragan Trough. This shallows to the north and west where it is bounded by the Beagle Ridge. To the south, the Dandaragan Trough is bounded by the Harvey Ridge and Bunbury Trough. Offshore and to the north, the Edel, Abrolhos and Houtman Sub-basins collectively contain sediments which extend from the Early Permian to the Early Cretaceous. Offshore and to the south, the Vlaming Sub-basin consists of about 10 km of Cretaceous and Tertiary sediments.

The structural history of the basin is recognised as being very complex with none of the existing models giving completely satisfactory explanations for all tectonic elements (Tupper *et al.,* 1994). There are considerable problems in accurately dating the Permian sections and this adds to the difficulties in reconstruction. Mory and Iasky (1994) recognise two major phases in the structural evolution of the Perth Basin. The first of these began with a north-south extension in the Early Permian resulting in east-west normal faulting and probable sinistral strike-slip along the Darling Fault. The Early Cretaceous break-up (132Ma) of the Greater India and Australia plates with associated extension, further fault movement and heating mark the second phase. Movement on the Darling Fault has probably always been a key issue in the balance between the tectonic and sea level controls on sedimentation.

Stratigraphy and Petroleum Systems

A generalised stratigraphy for the Perth Basin is shown in **Figure II-38**. The pre-rift sedimentary sequence comprises mainly Early Permian glacio-marine sediments (Carynginia Formation) interrupted by limited and localised coal-bearing sands (Irwin River Coal Measures). Rifting occurred in the Late Permian and was followed by local uplift and erosion. The post-rift sequence comprises the Wagina Sandstone and Beekeeper Formation. Following further erosion of the Permian rocks, an Early Triassic marine incursion took place over the northern Perth Basin resulting in deposition of the Kockatea Shale with its distinctive basal transgressive sandstone. The geographic distribution of the basal Triassic sandstone depocentres, being on the flanks of the Wagina Sandstone, suggests that a significant proportion of this unit was reworked from the crest of Late Permian alluvial fans. Following deposition of the Kockatea Shale, there was a long-lasting stage of Triassic paralic to fluvial sedimentation resulting in the Woodada Formation and Lesueur Sandstone with significant thickening of this latter unit

to the south and east of the Beagle Ridge. Further fluvial sedimentation took place in the Jurassic with deposition of the Eneabba Formation which thins onto the Beagle Ridge but has a notable depocentre in the Dandaragan Trough, adjacent to the Beagle Fault. This depocentre continued to be active during deposition of the marginal marine Cattamarra Coal Measures Member with a peak in transgression in the Middle Jurassic represented by the Cadda Formation marine shales and limestones. The Middle Jurassic to Early Cretaceous saw a sudden change back to fluvial and lacustrine sedimentation with resultant great thickness of the Yarragadee and Parmelia Formations. These sediments are interpreted to represent the second major rifting phase of the basin and mark the break-up of the Australian and Greater Indian Plates.

Petroleum accumulations within the Perth Basin originate from at least four stratigraphic horizons within the Gondwanan and Austral Supersystems (Bradshaw *et al*., 1994). The Gondwanan Supersystem includes fully terrestrial source rocks of the Early Permian Irwin River Coal Measures and some marine mudstone source rocks of the Early Permian Carynginia Formation, Permian Wagina Sandstone and Early Triassic Kockatea Shale (Warris, 1988). Organic matter in these sediments is considered to be the source of gas, condensate and oil in the Beharra Springs, Mondarra, Woodada, Dongara, Mount Horner and Whicher Range Fields of the onshore Perth Basin (Thomas, 1979, 1982; Jefferies, 1984). In contrast, oil in offshore Gage Roads-1 is thought to originate from the Late Jurassic rift-related sediments of the Yarragadee and/or Parmelia Formations (Kantsler and Cook, 1979; Backhouse, 1984) within the Austral Petroleum Supersystem (Bradshaw *et al*., 1994). The Gingin and Walyering Gas Fields of the onshore Dandaragan Trough were probably sourced from the Cattamarra Coal Measures Member within the Austral Supersystem.

In the northern part of the basin around the Yardarino, Mount Horner, Mondarra, Woodada and Beharra Springs Gas and Oil Fields, the Early Triassic Kockatea Shale overlies the Late Permian syn-rift reservoir sediments of the Wagina Sandstone and an Early Permian succession comprising the Carynginia Formation and Irwin River Coal Measures (**Figure II-38**). Between the Northampton Block and the Beagle Ridge, where the Dongara Field is located, Kockatea Shale either directly overlies the Early Permian Carynginia Formation or an extremely condensed section of Wagina Sandstone. Organic matter from land-plants has been said to contribute prominently to oils from the north Perth Basin (e.g., Thomas and Brown, 1983). The oil-prone nature of the Kockatea Shale in this region has been reported by Powell and McKirdy (1973a; 1975), Kantsler and Cook (1979), Thomas (1979, 1982), Thomas and Brown (1983) and Jefferies (1984). The Kockatea Shale is a paralic marine sediment with a calcareous basal unit up to 40 m thick containing 2-3% Type II sapropelic organic matter derived mainly from marine phytoplankton. Plant-derived exinite has also been reported (Balme, 1963; 1968; Kantsler and Cook, 1979). Furthermore, this unit is considered to be mature or post-mature to the east of the Beagle Ridge and into the Dandaragan Trough. While some of the gas in these northern fields may also come from the Kockatea Shale, Powell and McKirdy (1973b) and Thomas and Brown (1983) concluded that the Carynginia

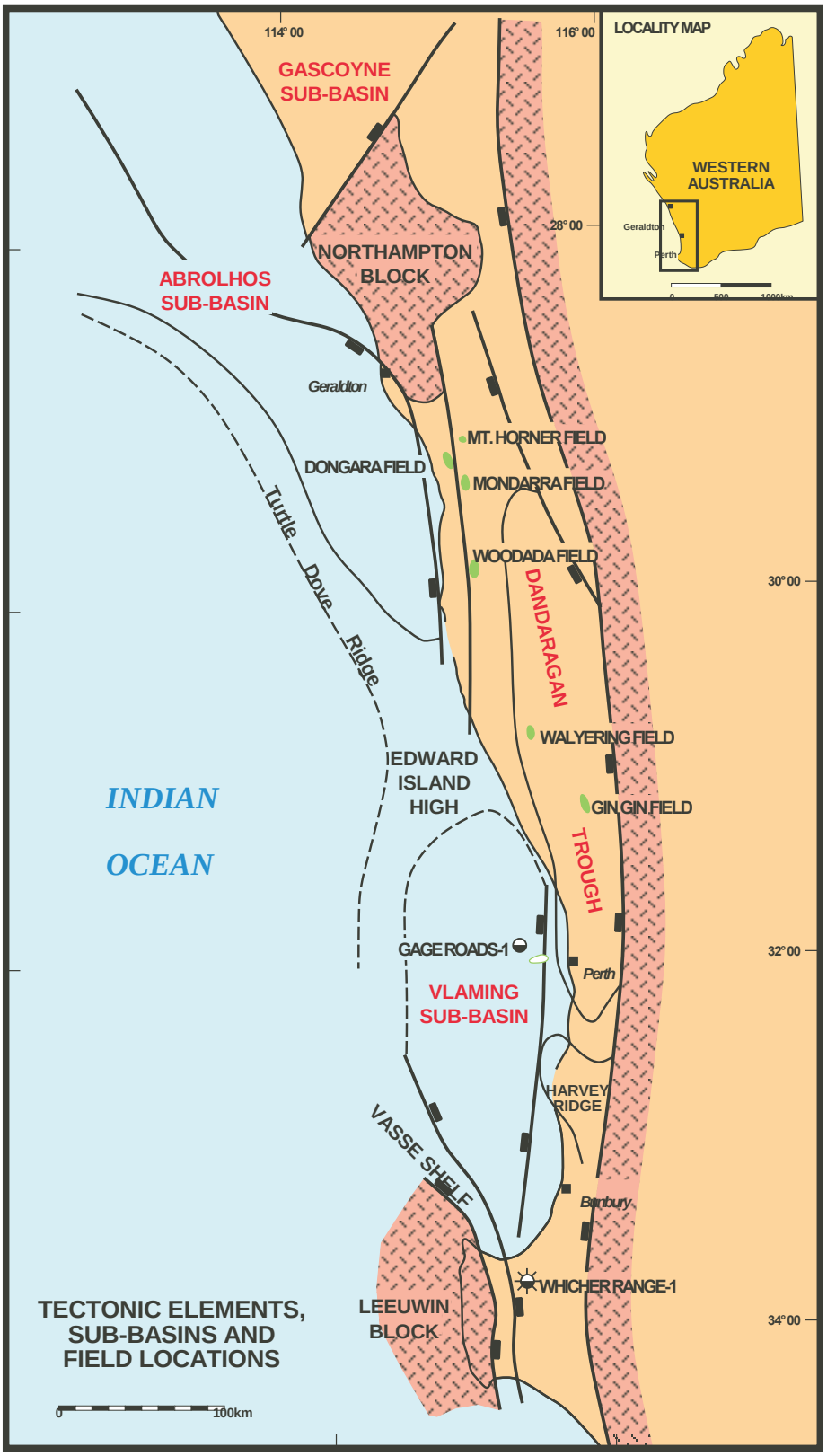


Figure II-37. Structural Element Map of the Perth Basin (Summons *et al*., 1995).

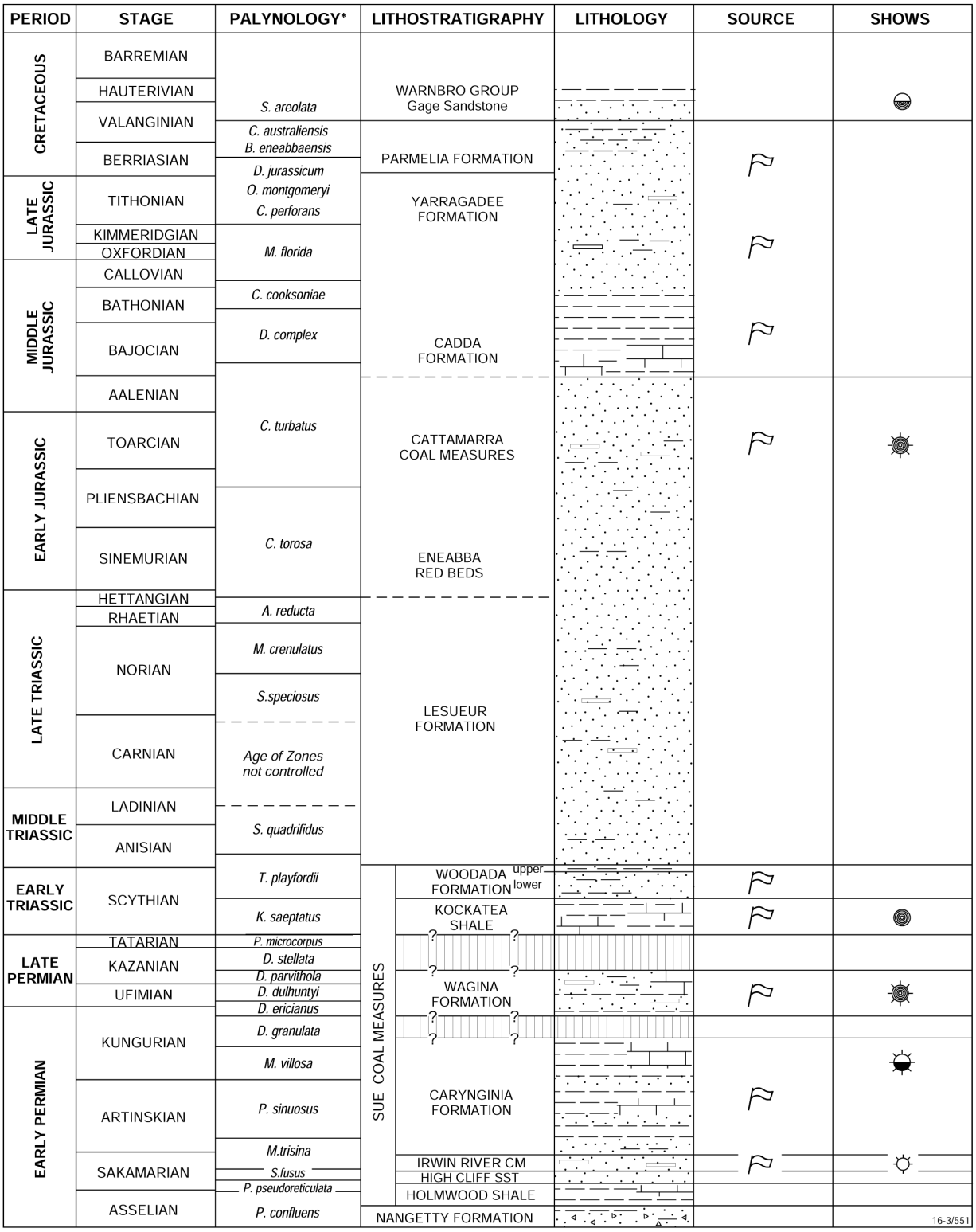


Figure II-38. Generalised Stratigraphy for the Perth Basin (Summons *et al*., 1995).

Formation and/or Irwin River Coal Measures are the principal sources of methane. The Permian Sue Coal Measures are thought to be the source of gas in Whicher Range-1 in the south Perth Basin. All these sediments have a high content of humic organic matter.

To the south and the east of the Beagle Ridge, the Dandaragan Trough is the location of the sub-commercial gas and condensate of the Walyering and Gingin Fields (**Figure II-37**). Here, the Triassic is overlain by a thick (up to 10,000 m) succession of Jurassic continental sediments, much of which has experienced temperatures sufficient for hydrocarbon generation (Thomas, 1982). The Early Jurassic Cattamarra Coal Measures Member of the Cockleshell Gully Formation has been assessed as having petroleum potential. The Late Jurassic Yarragadee Formation contains extensive lake deposits comprising shales and siltstones with moderate (up to 1.8%) organic carbon contents and possible oil potential. Condensates from the Walyering and Gingin Fields have intermediate Pr/Ph ratios between 2.8 and 5.2 consistent with this terrestrial input. Although geothermal gradients are low in the Dandaragan Trough, several studies (Kantsler and Cook, 1979; Thomas, 1982; Thomas and Brown, 1983) estimate that the top of the Cattamarra Coal Measures Member is in the mature zone for oil and gas generation in the vicinity of the Gingin and Walyering Fields.

To the west of the Beagle Ridge, the Vlaming Sub-basin also contains a thick Jurassic and Early Cretaceous succession (Spring and Newell, 1993). The sub-economic Gage Roads-1 oil is considered to have its source in these rocks (Kantsler and Cook, 1979; Backhouse, 1984) and consistent with this, the Late Jurassic Yarragadee Formation has reached appropriate maturity.

Recognition of effective source facies and their behaviour on thermal maturation are key aspects in evaluating risk in frontier basins and requires a firm understanding of stratigraphic relationships. The rarity of diagnostic Late Permian marine fauna in north Perth Basin sediments has hampered this and prevented correlation with marine sequences in other basins (Brakel and Totterdell, 1990; Archbold, 1994). Palynological studies are currently the principal means of chronological correlation but poor preservation and lack of suitable samples renders even these solutions imprecise (Tupper *et al.,* 1994). While the Kockatea Shale is unambiguously Early Triassic (Scythian) in age (McTavish and Dickins, 1974), the exact relationship between the base of the Kockatea Shale and Wagina Sandstone and between the Wagina Sandstone and Early Permian sediments, considered to be the source of gas, have been difficult to resolve. A combined palynolgical and chemostratigraphic analysis of core from the Woodada-2 well (Summons *et al*., 1995; Gorter *et al*., 1996) indicates that, despite there being a lithologically uniform black calcareous shale section covering the Permian to Triassic transition, a significant time break is present. Basal Triassic sediments containing reworked Permian organic matter rest on Early Permian sediments of a similar lithology which is consistent with the Late Permian erosional event in this region.

CHAPTER III
OIL GEOCHEMISTRY AND CORRELATION

Introduction

Location **Table 1** gives field, well, and reservoir data for the 160 crude oil samples collected from the various wells within the Bonaparte (31 samples), Carnarvon (87 samples), Browse (1 sample), Canning (13 samples), and Perth (20 samples) basins of western Australia. In addition, eight Indonesian oils from the Bintuni, Seram, and Timor areas are included for comparison. **Figure III-1** is a map of western Australia showing generalised locations of the fields/wells from which the various crude oil samples were obtained. In many cases, there are multiple oil samples from the same field which is crucial in determining analytical precision and reservoir heterogeneity. Some of these samples represent depth and/or reservoir age variations within one field, an important consideration when attempting to unravel migration and thermal histories, especially if more than one oil family (i.e., multiple source horizons) are present in a particular field. Also, there are a few oils from the same field and reservoir that were obtained from different sources which are important for sample verification. These fields include Jabiru, Barnett, Barrow Island, Goodwyn, Saladin, Rough Range, Erregulla, etc.

Bulk Characteristics

Appendix A lists API gravity, percent light ends (%<C15+), percent sulfur, nickel and vanadium concentrations for the crude oil samples included in this study. Gas chromatographic and stable carbon isotopic data are also listed in **Appendix A** and will be discussed in subsequent sections. In general, thermally mature oils tend to have high gravities and correspondingly high relative percentages of light ends; however, many geochemical processes, other than thermal maturity, are responsible for an oil's API gravity. The sample quality must also be considered (e.g., samples stored for a long time may have suffered substantial evaporative loss and samples which are oil/water emulsions may give false API gravity data). Since biodegradation tends to reduce the light ends due to preferential aerobic bacterial activity and associated water washing, a thermally mature, but biodegraded oil would have less light ends and a lower API gravity. Differential migration (light ends migrating preferentially to heavy ends) and reservoir deasphalting (due to a charge of gas into an oil reservoir) can also cause a change in API gravity. Many of the oils under consideration have rather high API gravities (> 45°) and can be classified as condensates.

Western Australia oils have very low sulfur concentrations with values seldom above 0.05% probably as a result of generation from thermally mature to very mature shales containing abundant terrigenous organic matter. **Figure III-2** is a plot of API gravity versus percent sulfur. In general, marine-derived crude oils have higher sulfur contents than oils generated from sediments deposited in lacustrine or near shore marine environments. However, since sulfur content is highly dependent upon thermal maturity, low maturity terrigenous oils may have more sulfur than higher maturity marine oils.

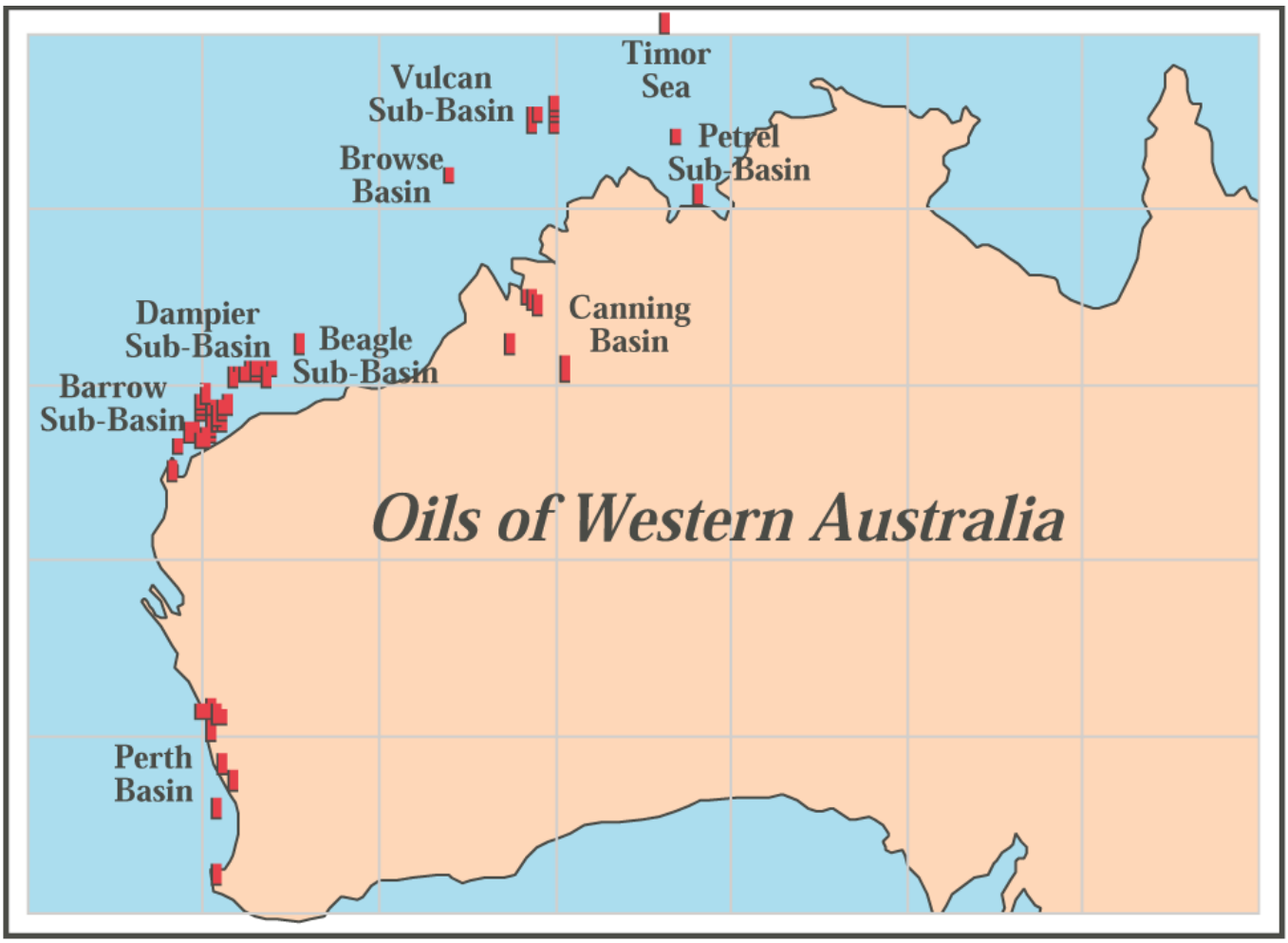


Figure III-1. Sample location map.

Table III-1. Location and Reservoir Data.

ID	Basin	Field	Well	Depth	Age	Formation	AGSO ID	Lat	Long
AU351	Bonaparte	Barnett	2; DST 1?		Carboniferous	Milligans	AGSO-10015	-14.5323	129.0522
AU352	Bonaparte	Barnett	2; DST 3?		late Carboniferous/E. Permian	U. Kuriyippi/Kulshill	AGSO-10016	-14.5323	129.0522
AU353	Bonaparte	Petrel	4				AGSO-10017	-12.8884	128.4948
AU029	Bonaparte/Petrel	Barnett	2; DST 1	2393-2408 m	Carboniferous	Milligans	AGSO-439	-14.532314	129.05221
AU030	Bonaparte/Petrel	Barnett	2; DST 3	1491-1497 m	late Carboniferous/E. Permian	U. Kuriyippi/Kulshill Gp.	AGSO-440	-14.532314	129.05221
AU031	Bonaparte/Petrel	Barnett	2; DST 4	1500.5-1506.5 m	late Carboniferous/E. Permian	U. Kuriyippi/Kulshill Gp.	AGSO-441	-14.522314	129.05221
AU032	Bonaparte/Petrel	Turtle	1; DST 5	1618.9-1621 m	late Carboniferous/E. Permian	U. Kuriyippi/Kulshill Gp.	AGSO-382	-14.47661	128.94484
AU033	Bonaparte/Petrel	Turtle	2; RFT	927.1 m	Early Permian	Keyling/Kulshill Gp.	AGSO-383	-14.505891	128.94581
AU034	Bonaparte/Petrel	Turtle	2; DST 1A	2632-2721 m	Carboniferous	Tanmurra-Milligans	AGSO-384	-14.50589	128.94581
AU035	Bonaparte/Vulcan	Talbot	1; DST 1	1505-1540 m	Late Triassic	Challis/Sahul Gp.	AGSO-522	-12.453166	124.88158
AU036	Bonaparte/Vulcan	Challis	1; PROD	1390.5-1403.5 m	Middle-LateTriassic	CS 2.3/Sahul Gp.	AGSO-508	-12.123753	125.00446
AU037	Bonaparte/Vulcan	Challis	3; DST 1	1380.9-1387 m	Middle-LateTriassic	CS 3.1/Sahul Gp.	AGSO-326	-12.115125	125.022888
AU038	Bonaparte/Vulcan	Challis	7; DST 1	1373.5-1379.5 m	Middle-LateTriassic	CS 5.4 & 4.1/Sahul Gp.	AGSO-532	-12.105367	125.04056
AU039	Bonaparte/Vulcan	Challis	8; DST 1	1393.5-1409.5 m	Middle-LateTriassic	CS 6.1/Sahul Gp.	AGSO-533	-12.10216	125.04782
AU001	Bonaparte/Vulcan	Jabiru	PROD. TEST		Jurassic			-11.93	125.00
AU040	Bonaparte/Vulcan	Jabiru	1A; PROD 2	1608-1628 m	Early Jurassic	Plover/Troughton Gp.	AGSO-507	-11.933561	125.00408
AU041	Bonaparte/Vulcan	Jabiru	8A ST1; DST 1	1770-1780 m	Late Jurassic	Upper Vulcan/Swan Gp.	AGSO-530	-11.93652	125.01038
AU042	Bonaparte/Vulcan	Jabiru	11 ST 1; RFT 1	1657-1694 m	Late Jurassic	Upper Vulcan/Swan Gp.	AGSO-531	-11.94203	124.9933
AU002	Bonaparte/Vulcan	Puffin	2; DST 1	2028-2035 m	Late Cretaceous	Puffin/Borde Fm./Bath. I. Gp.		-12.36295	124.2754
AU003	Bonaparte/Vulcan	Puffin	3; WFT 2 or 3	2102-2103 m	Early Cretaceous	Puffin/Borde Fm./Bath. I. Gp		-12.28878	124.35825
AU043	Bonaparte/Vulcan	Puffin	1; RFT 1	2067 m	Late Cretaceous	Puffin/Borde Fm./Bath. I. Gp.	AGSO-232	-12.308333	124.333611
AU044	Bonaparte/Vulcan	Puffin	2; RFT 4	2032 m	Late Cretaceous	Puffin/Borde Fm./Bath. I. Gp.	AGSO-524	-12.36295	124.2754
AU045	Bonaparte/Vulcan	Skua	2; DST 1	2332-2336.5 m	Cretaceous	basal sst./Bathurst Is. Gp.	AGSO-525	-12.509516	124.40434
AU046	Bonaparte/Vulcan	Skua	3; DST 1	2376-2381 m	Middle Jurassic	Plover/Troughton Gp.	AGSO-526	-12.506121	124.41466
AU047	Bonaparte/Vulcan	Skua	8; Completion	2309-2340 m	Middle Jurassic	Plover/Troughton Gp.	AGSO-879	-12.509094	124.4067
AU048	Bonaparte/Vulcan	Skua	9 ST1; Completion 1	2313-2339 m	M. Jurassic	Plover/Troughton Gp.	AGSO-888	-12.498047	124.419972
AU049	Bonaparte/Timor	Sunrise	1; FIT 2	2195.5-2206 m	Late Jurassic	Flamigo/Flamingo Gp.	AGSO-499	-9.590097	128.15378
AU050	Bonaparte/Timor	Sunrise	1; FIT 2	2195.5-2206 m	Late Jurassic	Lower Flamingo	AGSO-504	-9.590097	128.15378
AU051	Bonaparte/Vulcan	Swan	1; WFT 1	2364 m	Late Cretaceous	Fenelan/Bathurst Is. Gp.	AGSO-416	-12.18816	124.49283
AU052	Bonaparte/Vulcan	Swan	3; RFT 3/4	2311-2329.5 m	Late Cretaceous	Puffin/Bathurst Is. Gp.	AGSO-887	-12.194375	124.491953
AU053	Bonaparte/Timor	Troubadour	1; DST 2	2228-2244 m	Late Jurassic	Flamingo	AGSO-460	-9.734394	128.12375
AU279	Browse	North Scott Reef	1; PROD TEST	4223-4283 m	Early Jurassic	unamed	AGSO-922	-13.94845	121.97543
AU140	Canning	Blina	2; DST 5	1470-1489 m	Late Devonian	Nullara Lst.	AGSO-358	-17.6186	124.4965
AU141	Canning	Blina	5; DST 2	1457-1472m	Late Devonian	Nullara Lst.	AGSO-359	-17.62638	124.50277
AU329	Canning	Blina	1; DST 2/3/8/13	1160-1813 m		Nullara or Yellow Drum	AGSO-10008	-17.623333	124.50139
AU142	Canning	Dodonea	1; DST 1	1519-1554 m	Ordovician	Goldwyer	AGSO-299	-19.38639	125.16083
AU143	Canning	Janpam North	1; DST 1	1644-1662 m	Late Devonian	Nullara Lst.	AGSO-360	-17.56833	124.41652
AU144	Canning	Lloyd	1; PROD TEST	1512-1523 m	Carboniferous	Anderson	AGSO-361	-17.46749	124.24916
AU145	Canning	Meda	1; DST 9A/9B/9C	1557-1564 m	late Carboniferous	Laurel	AGSO-395	-17.40000	124.19167
AU146	Canning	Mirbelia	1; DST 2	1837-1846.5 m	Devonian	Mellinjerie Lst.	AGSO-300	-19.65222	125.36029
AU147	Canning	Pictor	2: PROD TEST	929-956 m	Ordovician	Nita	AGSO-678	-18.76587	123.71362
AU148	Canning	Sundown	1; RFT 2	1098 m	Carboniferous	Grant	AGSO-362	-17.55277	124.24194
AU149	Canning	Sundown	4; DST 1/3/4/5	1169 -1480 m	Carboniferous	Grant or Anderson	AGSO-363	-17.5533	124.2408
AU150	Canning	West Terrace	1; DST 1	1147-1159 m	late Carboniferous/E. Permian	Grant	AGSO-364	-17.50722	124.25890
AU151	Canning	West Terrace	2	1198m	late Carboniferous/E. Permian	Lower Grant	AGSO-365	-17.50411	124.25969
AU360	Carnarvon/Barrow	Australind	1 RFT4	1218-1223m	Early Cretaceous	Barrow	AGSO-10038	-21.41502	115.03828
AU386	Carnarvon/Barrow	Bambra	2 DST3	2032-2033.5m	Early Cretaceous	Barrow Gr., Flag Mbr.	AGSO-10065	-20.5456	115.60066
AU387	Carnarvon/Barrow	Bambra	1 RFT1	3640.5m	Middle Jurassic	Biggada Sst.	AGSO-10066	-20.52623	115.63227
AU071	Carnarvon/Barrow	Barrow	1; DST 16	2057.4-2067.5 m	Late Jurassic	Unit D/ Dupuy Fm.?	AGSO-461	-20.81833	115.39388
AU072	Carnarvon/Barrow	Barrow Deep	1; PROD	3429 m	Middle Jurassic	Biggada Sst.	AGSO-056	-20.83530	115.38224
AU073	Carnarvon/Barrow	Barrow Island	15; PROD		Early Cretaceous	Windalia Sst. Mbr./Muderong	AGSO-399	-20.8522	115.3595
AU074	Carnarvon/Barrow	Barrow Island	17	2282.9-2312.2 m	Early Cretaceous	Windalia Sst. Mbr./Muderong	AGSO-166	-20.8453	115.3442
AU362	Carnarvon/Barrow	Barrow Island	1 L84M	Well Head	Early Cretaceous	Winning, Mardle	AGSO-10040	-20.82666	115.38111
AU363	Carnarvon/Barrow	Barrow Island	X53J	1692m	Early Cretaceous	Barrow	AGSO-10041	-20.72722	115.42639
AU370	Carnarvon/Barrow	Barrow Island	F81FL	Well Head	Early Cretaceous	Barrow Flacourt	AGSO-10048	-20.82	115.38
AU374	Carnarvon/Barrow	Barrow Island	L64MA	840.5-858.5m	Early Cretaceous	Winning, Muderong	AGSO-10052	-20.82152	115.38226
AU384	Carnarvon/Barrow	Campbell	1 RFT1	2216m	Early Cretaceous	Barrow Gr., Flag Mbr.	AGSO-10063		
AU075	Carnarvon/Barrow	Chervil	4; PROD	1384-1618 m	Early Cretaceous	Flacourt/Barrow Gp.	AGSO-799	-21.31099	115.22703
AU027	Carnarvon/Barrow	Chinook	1; RFT 2	2654 m	Early Cretaceous	Barrow "A" Fm.(Zeepard Fm.?)		-21.17009	114.69660
AU366	Carnarvon/Barrow	Crest	1 Well Head	1157.5-1159.5m	Early Cretaceous	Winning	AGSO-10044	-21.45511	115.01479
AU079	Carnarvon/Barrow	Elder	1; DST 1	1778.8-1786.8 m	Late Triassic	Mungaroo	AGSO-797	-21.31200	115.2314
AU056	Carnarvon/Barrow	Flag	1; DST 1	1270-1291 m	Early Cretaceous	Windalia SSt. Mbr./Muderong	AGSO-501	-20.46527	115.64565
AU080	Carnarvon/Barrow	Flinders Shoal	1; DST 1A	2597-2622 m	Early Cretaceous	Birdrong	AGSO-082	-21.07111	115.52166
AU371	Carnarvon/Barrow	Flinders Shoal	1 DST1/1A	792.58-799.2m	Early Cretaceous	Winning, Birdsong SS	AGSO-10049	-21.07111	115.52167
AU028	Carnarvon/Barrow	Griffin	1; DST 1	2656.5-2664 m	Early Cretaceous	Barrow "A" Fm.(Zeepard Fm.?)		-21.23562	114.61999
AU057	Carnarvon/Barrow	Harriet	A6; PROD	1900-1922m	Early Cretaceous	Flag Sst.	AGSO-602	-20.6036	115.6125
AU081	Carnarvon/Barrow	Harriet	A3; PROD	1902-1922 m	Early Cretaceous	Flag Sst.	AGSO-593	-20.6033	115.6128
AU082	Carnarvon/Barrow	Harriet	A5; PROD	1888-1910 m	Early Cretaceous	Flag Sst.	AGSO-594	-20.60333	115.61278
AU083	Carnarvon/Barrow	Harriet	B1; DST 2	1943.5 -1946 m	Early Cretaceous	Flag Sst.	AGSO-595	-20.6033	115.6125
AU084	Carnarvon/Barrow	Harriet	B3	1909.2-1916 m	Early Cretaceous	Flag Sst.	AGSO-596	-20.60332	115.6125

Table III-1. Location and Reservoir Data (cont.).

ID	Basin	Field	Well	Depth	Age	Formation	AGSO ID	Lat	Long
AU058	Carnarvon/Barrow	Hilda	1A; FIT 3	2669.5 m	Early Cretaceous	Barrow Gp	AGSO-126	-21.19985	114.63700
AU085	Carnarvon/Barrow	Hilda	1A; FIT 3	2669 m	Early Cretaceous	Barrow Gp	AGSO-500	-21.19985	114.63700
AU328	Carnarvon/Barrow	Maitland	1; DST 1/2	1266-1289 m	Tertiary?		AGSO-883	-20.5624	115.1742
AU087	Carnarvon/Barrow	North Herald	3; DST 1	1430-1735 m	Late Jurassic	Flacourt/Barrow Gp.	AGSO-349	-21.17524	115.26380
AU060	Carnarvon/Barrow	Pasco	1; DST8	1826-1832 m	Early Cretaceous	Malouet/Barrow Gp.	AGSO-051	-20.97194	115.32500
AU153	Carnarvon/Barrow	Pasco	1; DST 6	1750-1754 m	Early Cretaceous	Malouet?Barrow Gp.	AGSO-053	-20.97194	115.32500
AU383	Carnarvon/Barrow	Rosette	1 RFT2	2396m	Early Cretaceous	Barrow Gr., Flag Mbr.	AGSO-10062	-20.65658	115.57394
AU061	Carnarvon/Barrow	Saladin	8		Early Cretaceous	Barrow Gp.	AGSO-564	-21.4416	115.0531
AU090	Carnarvon/Barrow	Saladin	1; RFT 3	1128.7 m	Early Cretaceous	Flacourt/ Barrow Gp.	AGSO-297	-21.44161	115.05316
AU091	Carnarvon/Barrow	Saladin	2; PROD TEST	1110.5-1117 m	Early Cretaceous	Flacourt/ Barrow Gp.	AGSO-330	-21.44694	115.03944
AU092	Carnarvon/Barrow	Saladin	3; PROD TEST	1112.5-1116.4 m	Jurassic/Cretaceous	Barrow Gp	AGSO-329	-21.47102	115.02324
AU062	Carnarvon/Barrow	Sinbad	1; PROD	2027-2064 m	Early Cretaceous	Flag Sst.	AGSO-745	-20.48397	115.7105
AU063	Carnarvon/Barrow	South Pepper	1; DST 4	2214-2217 m	Early Cretaceous	Malouet/Barrow Gp	AGSO-881	-21.1249	115.27476
AU064	Carnarvon/Barrow	South Pepper	8		Early Cretaceous	Flacourt/Barrow Gp.	AGSO-520	-21.1247	115.2747
AU065	Carnarvon/Barrow	South Pepper	10		Early Cretaceous	Flacourt/Barrow Gp.	AGSO-521	-21.1248	115.2704
AU066	Carnarvon/Barrow	Spar	1; DST 4	2621-2630 m	Cretaceous	Flacourt/Barrow Gp.	AGSO-503	-20.61435	114.88503
AU385	Carnarvon/Barrow	Tanami	1 RFT	2180.5m	Early Cretaceous	Barrow Gr., Flag Mbr.	AGSO-10064	-20.65486	115.57976
AU382	Carnarvon/Barrow	Yammaderry	2 Well Head	1101m	Early Cretaceous	Barrow	AGSO-10060	-21.49078	114.98886
AU059	Carnarvon/Beagle	Nebo	1; DST 1	2664-2668 m	Middle Jurassic	Upper Calypso	AGSO-880	-18.7808	117.8275
AU093	Carnarvon/Dampier	Angel	1; DST 2	2685-2688 m	Late Jurassic/E. Cretaceous	Angel	AGSO-402	-19.5056	116.5967
AU094	Carnarvon/Dampier	Angel	2; DST 1A	2742-2751m	Late Jurassic	Angel	AGSO-457	-19.46624	116.65689
AU095	Carnarvon/Dampier	Angel	3; DST 3	2740-2748 m	Late Jurassic/E. Cretaceous	Angel	AGSO-101	-19.5418	116.6285
AU096	Carnarvon/Dampier	Central Gorgon	1; DST 3	4015-4033 m	Late Triassic	Mungaroo	AGSO-153	-20.4692	114.8092
AU054	Carnarvon/Dampier	Cossack	1	2890-2956 m	Late Jurassic	Angel	AGSO-894	-19.55604	116.49595
AU055	Carnarvon/Dampier	Cossack	1	2890-2956 m	Late Jurassic	Angel	AGSO-642	-19.55604	116.49595
AU097	Carnarvon/Dampier	Dockrell	1; DST 2	3004-3009 m	Late Triassic	Mungaroo	AGSO-889	-19.78798	115.77979
AU098	Carnarvon/Dampier	Dockrell	1; DST 1	2987-2995m	Late Triassic	Mungaroo	AGSO-896	-19.78798	115.77979
AU099	Carnarvon/Dampier	Dockrell	1; DST 1	2987-2995 m	Late Triassic	Mungaroo	AGSO-401	-19.78798	115.77979
AU100	Carnarvon/Dampier	Eaglehawk	1; DST 2	2750-2766 m	Late Triassic	Brigadier Beds	AGSO-061	-19.50825	116.27689
AU076	Carnarvon/Dampier	East Spar	1; DST1A	2513.7-2536.7 m	Early Cretaceous	Top Barrow. Gp.	AGSO-882	-20.70775	114.97974
AU077	Carnarvon/Dampier	East Spar	1; DST1A	2513.7-2536.7 m	Early Cretaceous	Top Barrow. Gp.	AGSO-798	-20.70775	114.97974
AU078	Carnarvon/Dampier	Echo	1; DST 1	2987-2993 m	Late Triassic	Mungaroo	AGSO-895	-19.71181	115.72269
AU101	Carnarvon/Dampier	Egret	1; DST 1	3119-3128 m	Late Jurassic/E. Cretaceous	Angel	AGSO-447	-19.50645	116.34713
AU102	Carnarvon/Dampier	Goodwyn	1; DST 1	2842-2847 m	Late Triassic	Mungaroo	AGSO-885	-19.69355	115.89544
AU103	Carnarvon/Dampier	Goodwyn	1; DST 1	2842-2847 m	Late Triassic	Mungaroo	AGSO-118	-19.69355	115.89544
AU104	Carnarvon/Dampier	Goodwyn	3; DST 3	2879-2891 m	Late Triassic	Mungaroo	AGSO-128	-19.73585	115.87785
AU105	Carnarvon/Dampier	Goodwyn	4; DST 2	2856-2903 m	Late Triassic	Mungaroo	AGSO-893	-19.69388	115.84836
AU106	Carnarvon/Dampier	Goodwyn	4; DST 2	2856-2903 m	Late Triassic	Mungaroo	AGSO-109	-19.69388	115.84836
AU107	Carnarvon/Dampier	Goodwyn	5; PROD TEST	2835-2903 m	Late Triassic	Mungaroo	AGSO-890	-19.6783	115.89583
AU108	Carnarvon/Dampier	Goodwyn	7; PROD TEST	2812-2835 m	Late Triassic	Mungaroo	AGSO-884	-19.62835	115.96022
AU109	Carnarvon/Dampier	Gorgon	1; DST 4	3973-4002 m	Late Triassic	Mungaroo	AGSO-154	-20.57867	114.77274
AU110	Carnarvon/Dampier	Lambert	1;DST 1A	3101-3106 m	Late Jurassic	Angel	AGSO-886	-19.45643	116.48971
AU111	Carnarvon/Dampier	Lambert	1;DST 1A	3101-3106 m	Late Jurassic	Angel	AGSO-102	-19.4564	116.4897
AU152	Carnarvon/Dampier	Legendre	1; DST 2	1893-1898 m	Early Gretaceous	Barrow Gp	AGSO-089	-19.67194	116.73208
AU112	Carnarvon/Dampier	North Gorgon	1; DST 4	3740.5-3758.5m	Late Triassic	Mungaroo	AGSO-475	-20.38448	114.86155
AU113	Carnarvon/Dampier	North Rankin	4; DST1	2980-2998 m	M. Jurassic	Legendre	AGSO-074	-19.58516	116.11164
AU114	Carnarvon/Dampier	North Rankin	A; PROD		Late Triassic/E. Jurassic	Mungaroo	AGSO-891	-19.585	116.112
AU115	Carnarvon/Dampier	Rankin	1; FIT 8	2954 m	Triassic	Mungaroo	AGSO-233	-19.7989	115.7421
AU116	Carnarvon/Dampier	Talisman	1; DST 1B	1961-1968 m	Late Jurassic/Early Cretaceous	Angel	AGSO-283	-19.4954	116.9399
AU117	Carnarvon/Dampier	Talisman	1; DST 2	1945.5-1957 m	Late Jurassic/Early Cretaceous	Angel	AGSO-284	-19.4954	116.9399
AU118	Carnarvon/Dampier	Talisman	1; DST 3	1917.5-1927 m	Early Cretaceous	Muderong	AGSO-285	-19.4954	116.9399
AU119	Carnarvon/Dampier	Tidepole	1; WFT 10	3017.7 m	Late Triassic	Mungaroo	AGSO-400	-19.7687	115.8849
AU067	Carnarvon/Dampier	Wanaea	1; RFT 1	2896.5 m	Late Jurassic/Early Cretaceous	Angel	AGSO-643	-19.59313	116.43405
AU068	Carnarvon/Dampier	Wanaea	2; PROD	2897-2910 m	Late Jurassic/Early Cretaceous	Angel	AGSO-644	-19.61372	116.41123
AU069	Carnarvon/Dampier	Wanaea	4	2902-2918 m	Late Jurassic/Early Cretaceous	Angel	AGSO-892	-19.63123	116.39546
AU120	Carnarvon/Dampier	West Tryal Rocks	2; DST 3	3295-3305 m	Late Triassic	Mungaroo	AGSO-149	-20.21568	115.0654
AU121	Carnarvon/Dampier	West Tryal Rocks	3; DST 3	3434-3448 m	Late Triassic	Muderong	AGSO-466	-20.15496	115.04905
AU338	Carnarvon/Exmouth	Leatherback	1				AGSO-943	-21.6856	114.3652
AU388	Carnarvon/Exmouth	Leatherback	1 DST1	1751.3-1752.5m	Triassic	Mungaroo	AGSO-10067	-21.68555	114.36515
AU021	Carnarvon/Exmouth	Rough Range	1; DST 1	1098.8-1101.8 m	Late Cretaceous	Birdrong Sandstone		-22.41999	114.08333
AU088	Carnarvon/Exmouth	Rough Range	1; DST1	1099-1102 m	Cretaceous	Birdrong Sst./Winning Gp.	AGSO-224	-22.41719	114.081373
AU089	Carnarvon/Exmouth	Rough Range	1A		Early Cretaceous	Birdrong Sst./Winning Gp.	AGSO-227	-22.25305	114.08388

Table III-1. Location and Reservoir Data (cont.).

ID	Basin	Field	Well	Depth	Age	Formation	AGSO ID	Lat	Long
AU122	Perth	Dongara	14	1646 m	Early Triassic	Kockatea Shale	AGSO-405	-29.22555	115.01749
AU138	Perth	Dongara	4; PROD TEST 1	1719-1720 m	Early Permian	Irwin River Coal Measures	AGSO-407	-29.23055	114.98222
AU367	Perth	Dongara	14 DST1	1735-1753m	Triassic	Basal Sandstone	AGSO-10045	-29.22565	115.01749
AU368	Perth	Dongara	4 DST1	1685.24-1690.75m	Triassic	Basal Sandstone	AGSO-10046	-29.23055	114.98222
AU123	Perth	Erregulla	1; Swab Test	3174-3181 m	Early Jurassic	Cocleshell Gully	AGSO-485	-29.37722	115.39749
AU369	Perth	Erregulla	1 Swab Test	3173.32-3180.63m	Early Jurassic	Cockel Shell Gully	AGSO-10047	-29.37444	115.39583
AU124	Perth	Gage Roads	1; DST 1A/2A	1760-1782 m	Early Cretaceous	Gage Sst Mbr/ Perth Fm.	AGSO-190	-31.95578	115.3773
AU125	Perth	Gingin	1; DST 13	3871-3879 m	Early Jurassic	Cockleshell Gully	AGSO-404	-31.14305	115.82722
AU126	Perth	Mondarra	1; DST 2	2698-2700 m	Early Triassic	Basal sand	AGSO-127	-29.30163	115.11666
AU127	Perth	Mondarra	2; PROD TEST	2736-2740 m	Early Triassic	Basal sand	AGSO-234	-29.3525	115.10333
AU128	Perth	Mondarra	3; DST 1	2836-2845 m	Early Triassic	Basal sand	AGSO-408	-29.29333	115.11277
AU129	Perth	Mount Horner	1; DST 4	1484-1490 m	Early Triassic	Kockatea Shale	AGSO-409	-29.12833	115.08499
AU130	Perth	North Erregulla	1; DST 1	2919-2930 m	Early Triassic	Kockatea Shale	AGSO-413	-29.23861	115.32694
AU131	Perth	Walyering	1; PROD TEST 3	3368-3399 m	Early Jurassic	Cockleshell Gully	AGSO-125	-30.71583	115.46527
AU132	Perth	Walyering	2; TEST 4	3982-3997 m	Early Jurassic	Cockleshell Gully	AGSO-411	-30.71583	115.46527
AU133	Perth	Whicher Range	1; DST 7	4200-4205 m	Permian	Nangetty/Sue Coal M.	AGSO-414	-33.83861	115.37166
AU134	Perth	Woodada	3	2390-2500?	Permian/E. Triassic	Carynginia	AGSO-186	-29.75472	115.15583
AU135	Perth	Yardarino	1; DST 3	2299-2323 m	Late Permian	Wagina	AGSO-047	-29.22194	115.0550
AU136	Perth	Yardarino	1; DST 3	2299-2323 m	Late Permian	Wagina	AGSO-090	-29.22194	115.0550
AU137	Perth	Yardarino	1; DST 3	2299-2323 m	Late Permian	Wagina	AGSO-410	-29.22194	115.0550
ID120	Bintuni	Jagiro	4	229-255 m	Mio/Plio	Klasafet		-1.9	135.2
ID119	Bintuni	Mogoi	41		Miocene	Kais		-1.9	135.2
ID118	Bintuni	Wasian	24	846-1055 m	Miocene	Kais		-1.9	135.2
ID157	Bintuni	Wiriagar			L. Miocene	Kais		-2.1	134.9
ID176	Seram	Bula	2Y5					-3.4	130.7
ID139	Seram	Nief East	1	1742-1756 m	Late Jurassic	Manusela		-3.4	130.7
ID123	Timor	Aliambata	Seep	Surface	Cret/Pal	Borolalo		-8.5	127
ID122	Timor	Paulaca	Seep	Surface	Triassic	Aitutu		-8.5	127

The trend shown in **Figure III-2** reflects both variations in thermal maturity and source rock type. If Fe is not available to tie up the H_2S (as pyrite) present in reducing depositional environments, as is often the case during clastic deposition as opposed to carbonate environments, then the sulfur can become incorporated within the organic matter, eventually generating high sulfur crudes (> 1%) from the resulting sulfur-rich kerogen. For example, although not shown in **Figure III-2**, the two carbonate-sourced oils from the Seram basin in Indonesia (ID139 and ID176) contain over 3% sulfur.

Nickel and Vanadium concentrations are also very low for most of the samples from western Australia, often under 1 ppm, again reflecting moderate to high levels of thermal maturity. Ni/V ratios sometime reflect source variations, although the low concentration levels of these metals may not have the required precision and accuracy to assess significant source differences. In general, western Australia oils have more Ni than V, perhaps reflecting terrestrially-influenced depositional environments.

Gas Chromatography

Figures III-3a to **III-3e** illustrate examples of whole crude gas chromatograms which yield C15+ n-paraffin and isoprenoid hydrocarbon distributions. Lighter end gasoline range compounds are also observed but can sometimes be unreliable as useful indicators since different degrees of evaporation of the light ends can occur during collection and/or storage. A number of samples, however, were analysed for gasoline range components, especially the C7 isomers. These can be useful correlation parameters for high gravity oils and condensates.

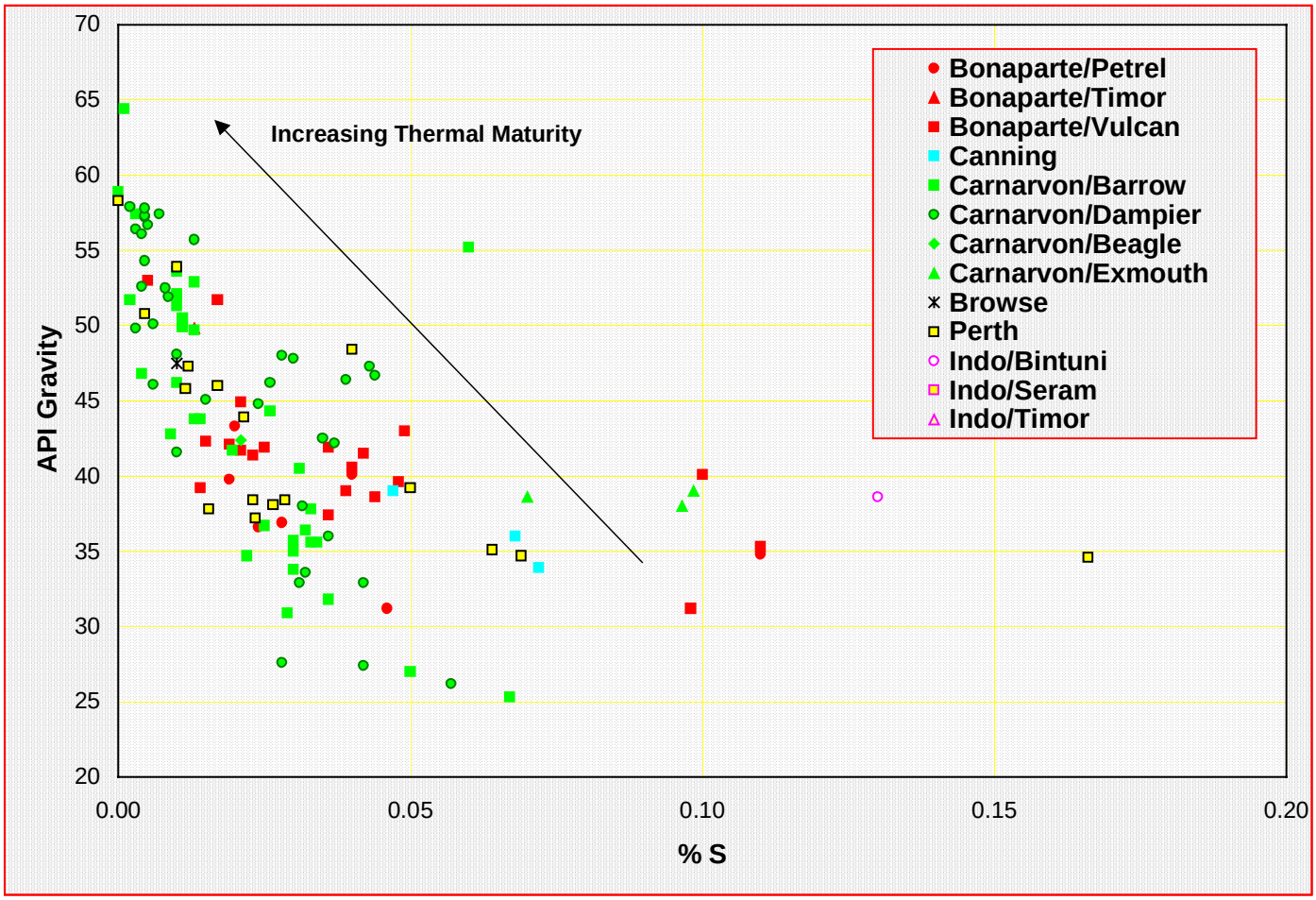


Figure III-2. API gravity versus % sulfur.

In **Figure III-3a**, Jabiru and Barnett (Bonaparte Basin) whole crude gas chromatograms are contrasted. The Jabiru oil has higher pristane to phytane (Pr/Ph) and *n*-C27 to *n*-C17 ratios than the Barnett oil suggesting a larger terrigenous component in the source kerogen in the former. Canning Basin gas chromatograms (**Figure III-3b**) often yield unique *n*-paraffin distributions highly characteristic of oils generated from Ordovician source rocks world-wide that contain the algae *G. prisca*. This can be seen in the Ordovician-reservoired Dodonea oil in which *n*-C17 and *n*-C19 are unusually abundant. Low amounts of isoprenoids (Pr and Ph) are also characteristic of Ordovician oils. In contrast, the Sundown oil chromatogram from a Carboniferous reservoir does not show the Ordovician signature suggesting another source.

Two Barrow Island oil chromatograms from the Carnarvon Basin are illustrated in **Figure III-3c**. The Barrow Island-17 oil from 2283 m shows no sign of biodegradation while the shallow (841 m) oil from L64M appears moderately biodegraded. The *n*-paraffins have been preferentially removed relative to the isoprenoids due to aerobic bacteria in the reservoir which must be in contact with fresh meteoritic waters containing oxygen and nutrients. Two Carnarvon Basin oil chromatograms from the Dampier sub-basin show little genetic difference (Talisman and Cossack oils; **Figure III-3d**). The increase in lighter end components in the Cossack oil could well be the result of thermal maturity differences; the Cossack oil has an API gravity of 48° while the Talisman oil is 42°. The Perth Basin Gage Roads oil contains abundant C15+ waxy paraffins suggestive of large land plant source component (**Figure III-3e**). Although the Dongara has lost light ends, the chromatogram looks more marine in character than Gage Roads.

Figure III-4 is a cross plot of the isoprenoid ratio Pr/Ph versus n-paraffins C27/C17. The Pr/*n*-C17 ratio is affected by other processes besides source, especially biodegradation and thermal maturity (increases due to the former and decreases because of the latter). Pr/Ph ratios, however, only increase slightly with thermal maturity, and their values often depend primarily upon source. Generally, high Pr/Ph values relate to a high terrigenous source component while low values imply more of a marine source environment. *n*-C27/*n*-C17 is one measure of the degree of 'waxiness' with higher values associated with terrigenous organic matter. This ratio will decrease at higher levels of thermal stress.

Many Perth and Exmouth Basin oils tend to have the most waxy oils suggestive of vascular land plants. Some Canning Basin oils have the lowest Pr/Ph values, often less than one, suggestive of highly reducing depositional environments of the corresponding source rock. The Petrel sub-basin oils have much lower Pr/Ph ratios than the Vulcan sub-basin oils in the Bonaparte meaning differences in source rock. In contrast, Barrow sub-basin oils and Dampier sub-basin oils in the Carnarvon Basin do not give significantly different gas chromatographic patterns that would allow facile discrimination.

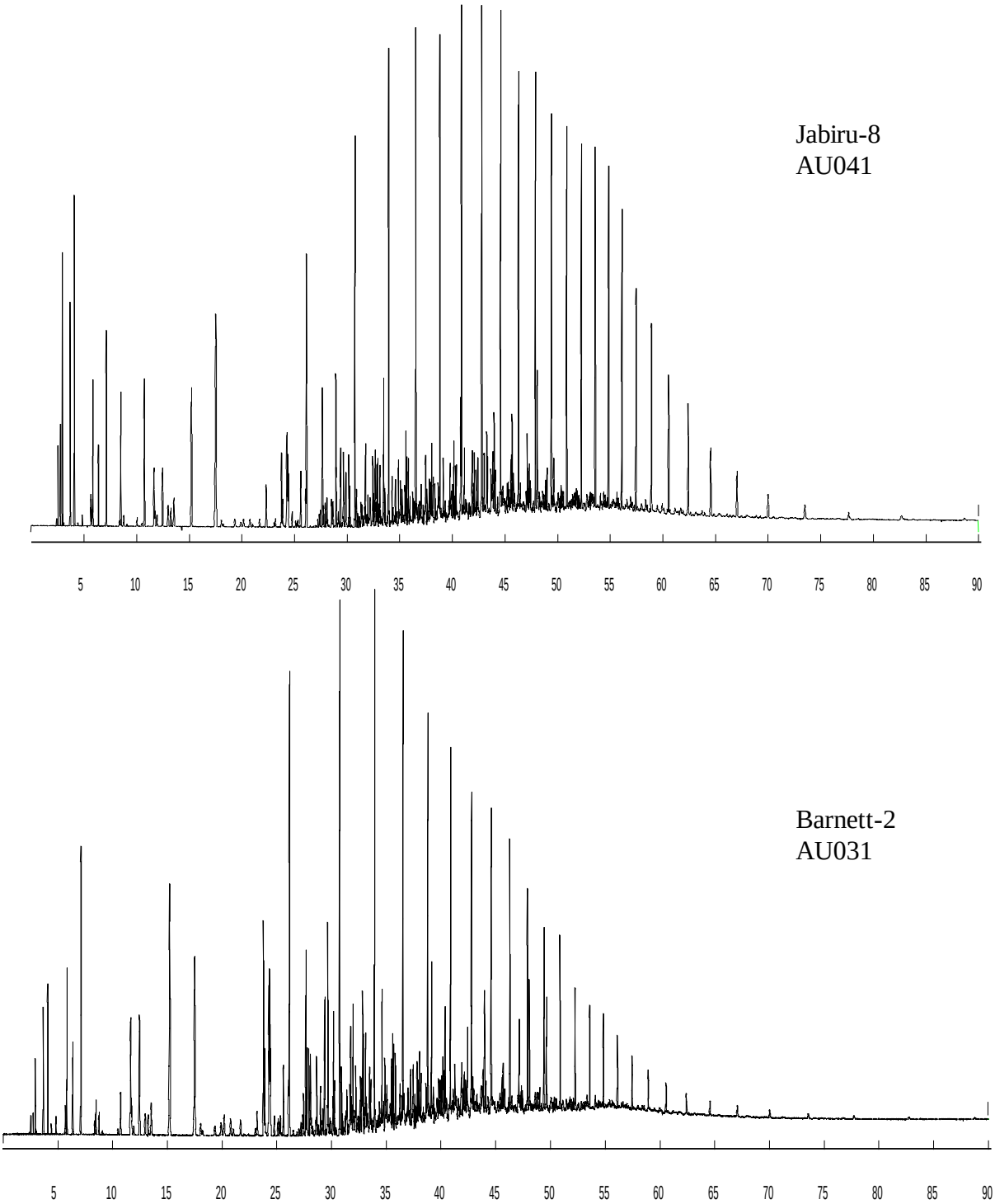


Figure III-3a. Whole Crude Gas Chromatograms from the Bonaparte Basin: Jabiru (AU041) and Barnett (AU031) Fields.

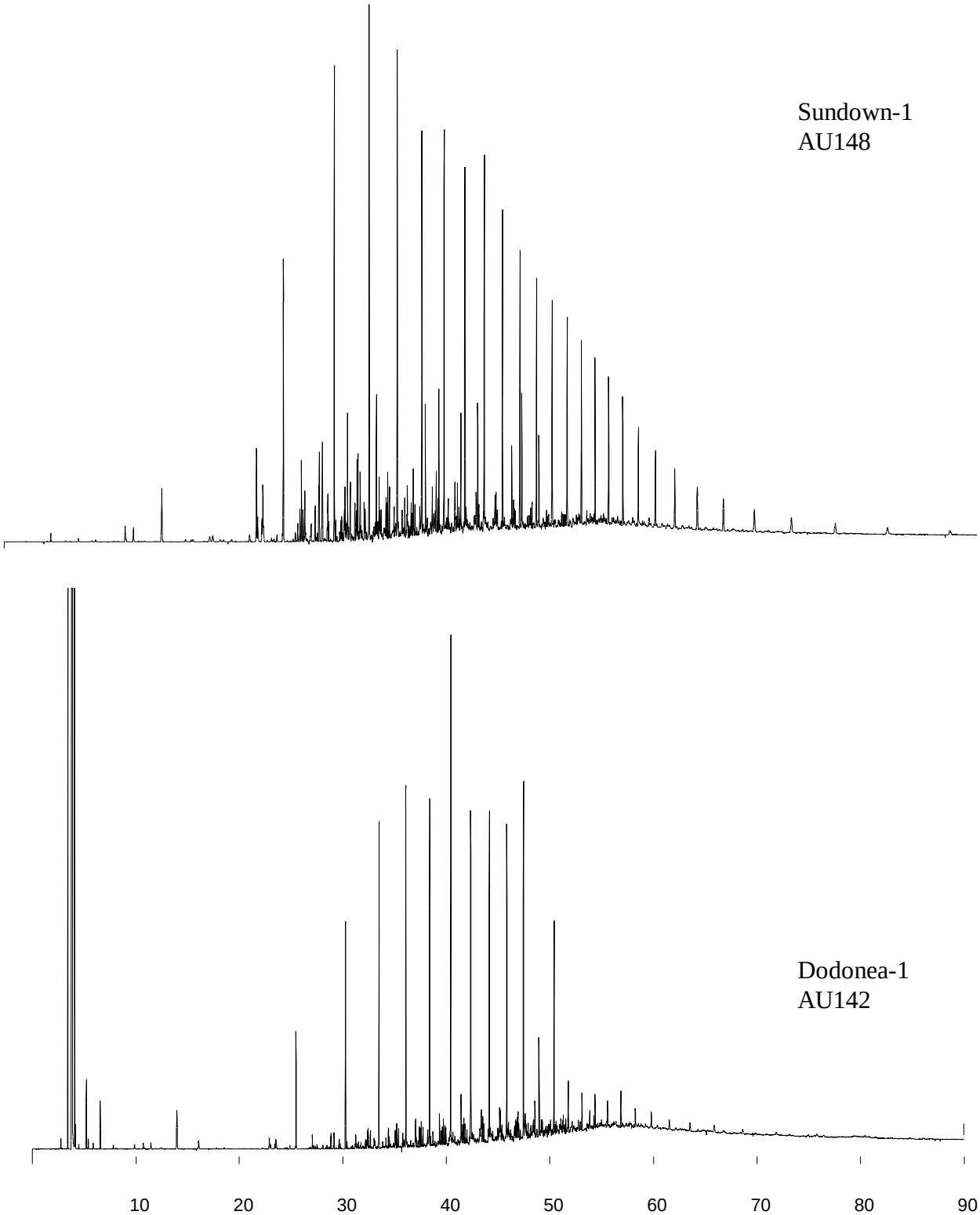
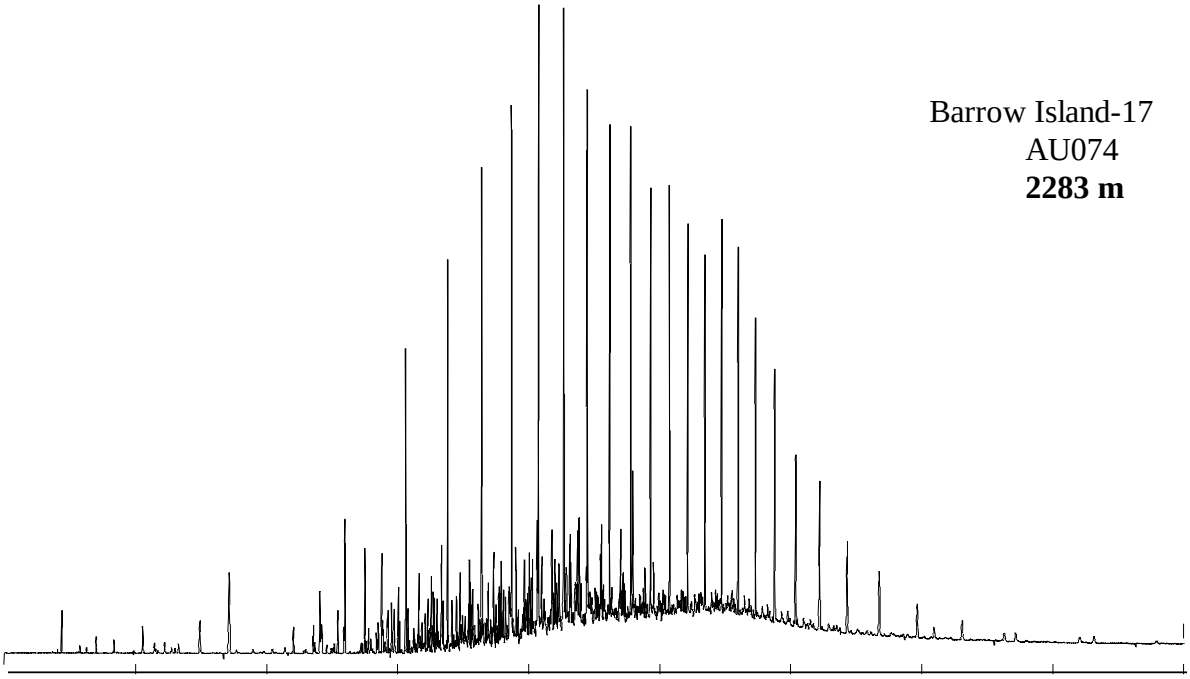


Figure III-3b. Whole Crude Gas Chromatograms from the Canning Basin: Sundown (AU148) and Dodonea (AU142) Fields.



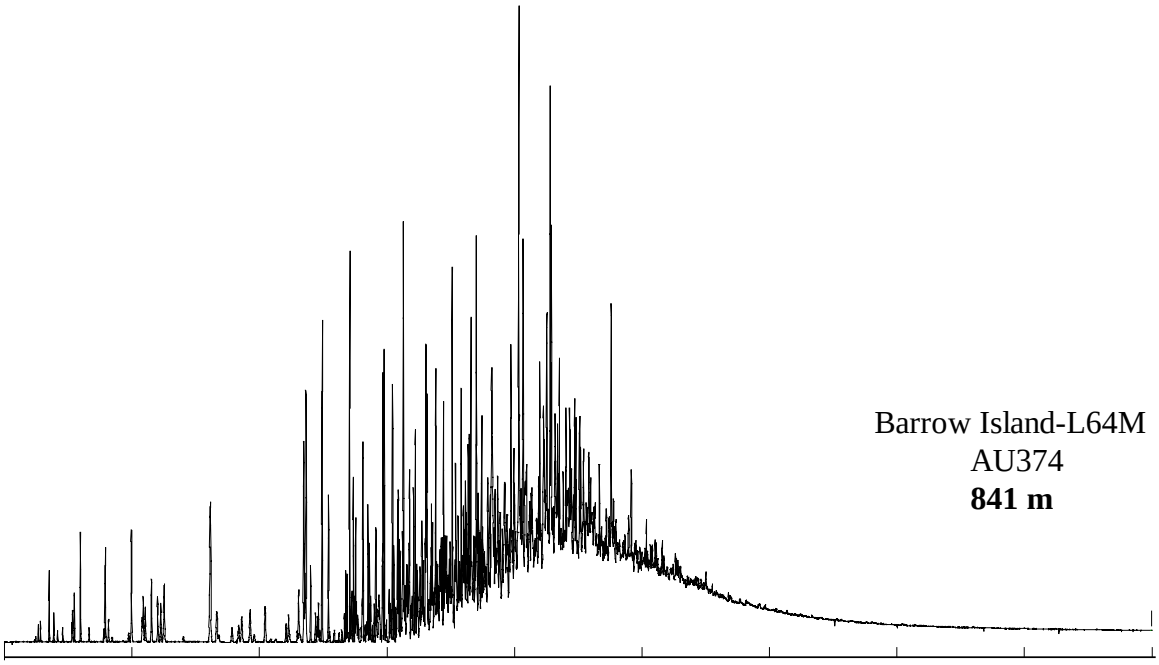
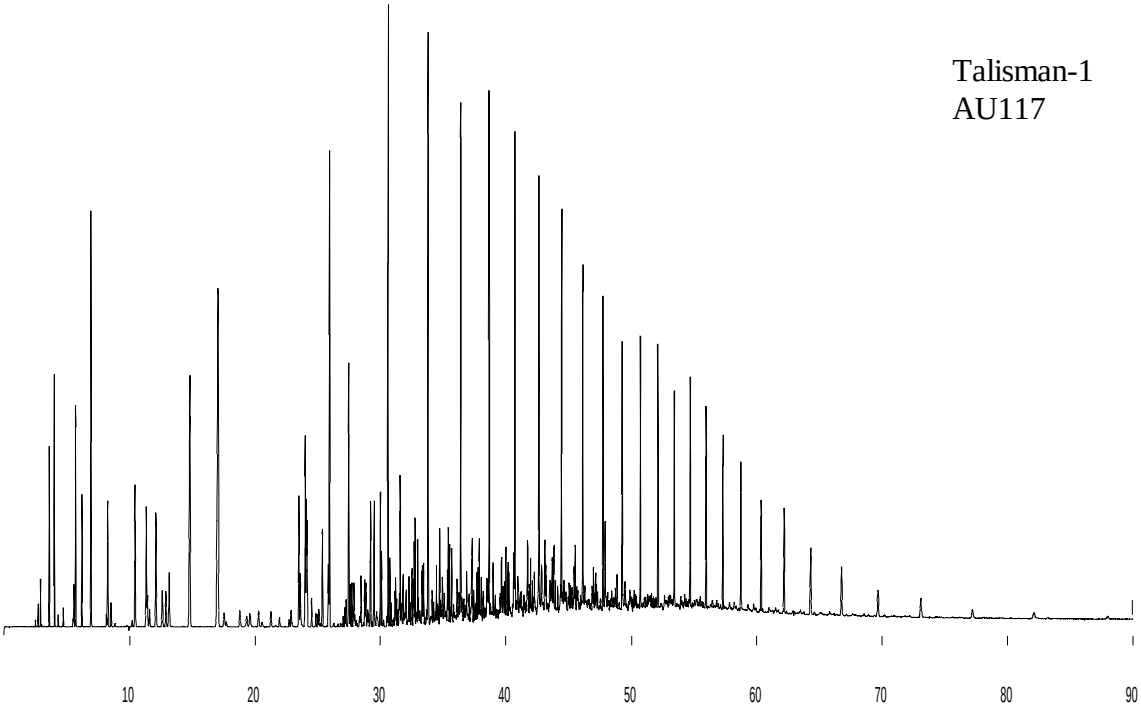


Figure III-3c. Whole Crude Gas Chromatograms from the Carnarvon Basin: Barrow Island (AU074 and AU374) Field.



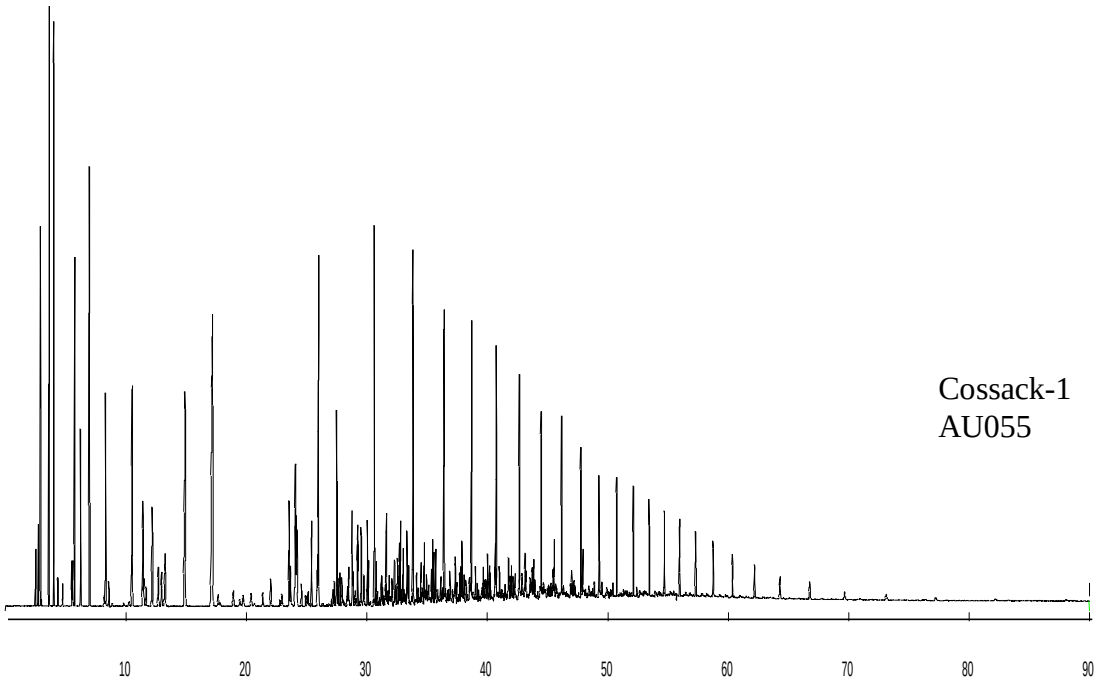


Figure III-3d. Whole Crude Gas Chromatograms from the Carnarvon Basin: Talisman (AU117) and Cossack (AU055) Fields.

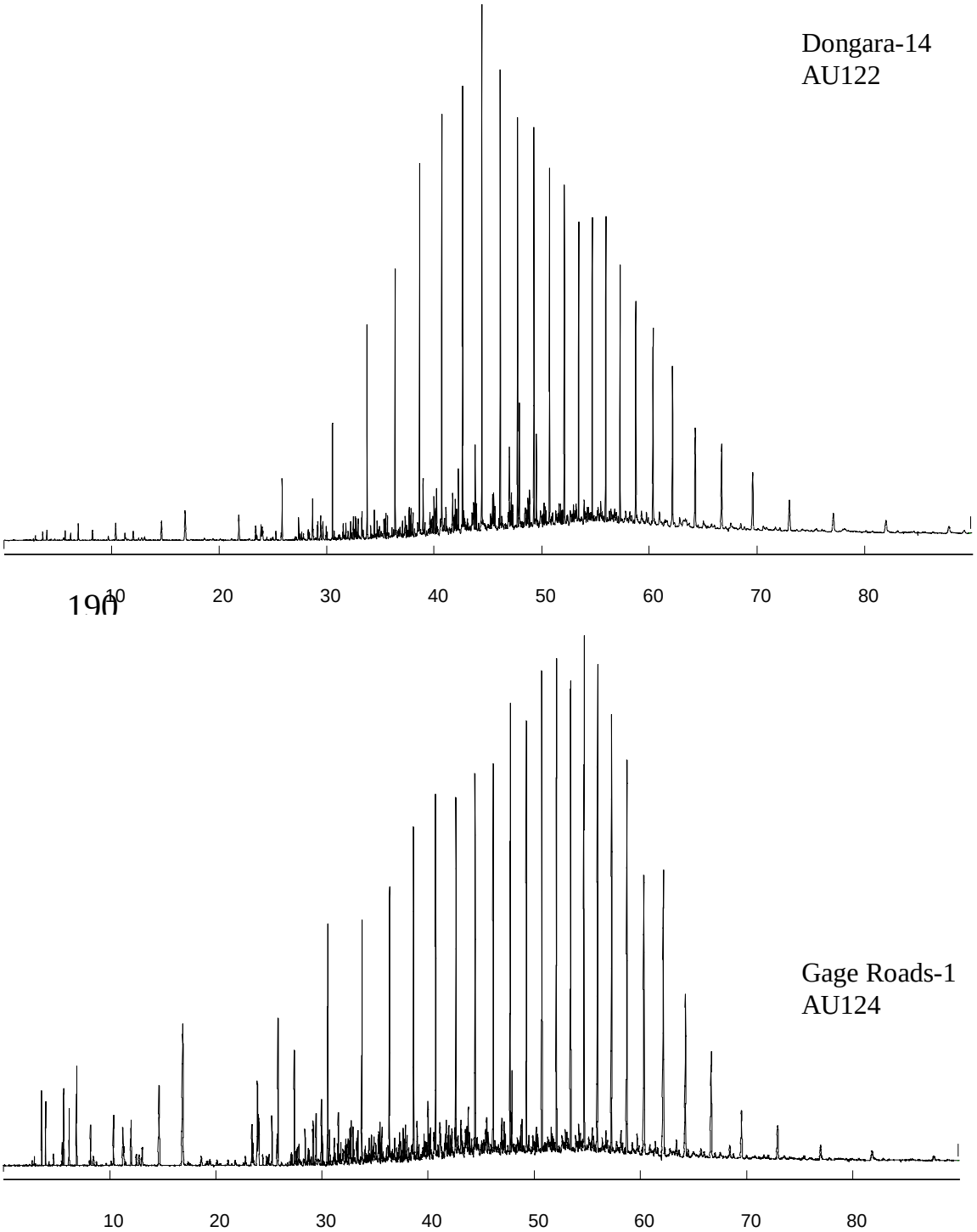


Figure III-3e. Whole Crude Gas Chromatograms from the Perth Basin: Dongara (AU122) and Gage Roads (AU124) Fields.

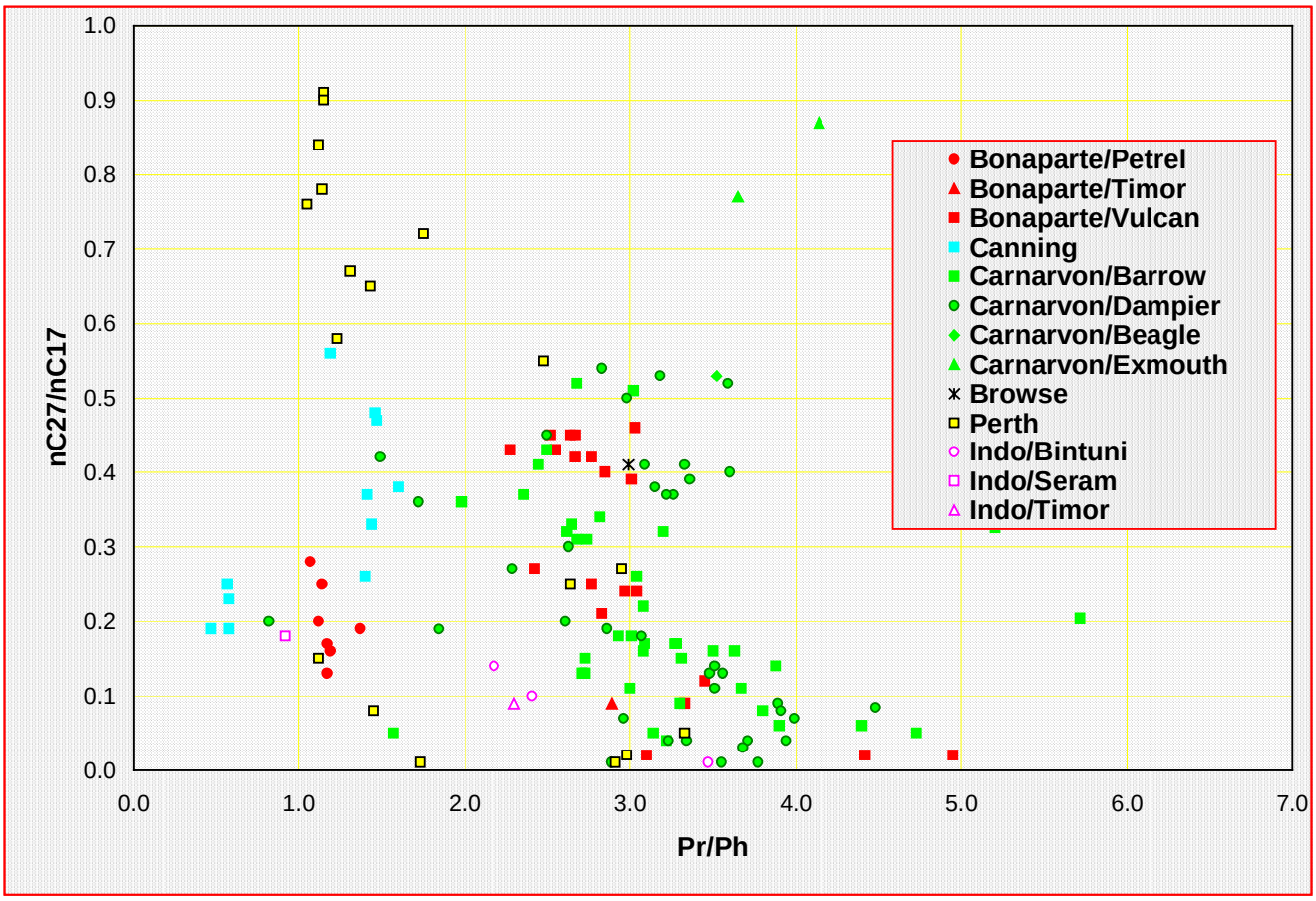


Figure III-4. Pristane/Phytane versus 'Waxy' Factor.

Stable Carbon Isotopes

The stable carbon isotope compositions of the C15+ saturate and aromatic hydrocarbon fractions of the oils from western Australia are plotted in **Figure III-5**. The stable carbon isotopic composition of crude oils is primarily dependent upon source. In addition, the difference in isotopic composition between the saturate and aromatic hydrocarbon fractions is suggestive of source depositional environment as shown by Sofer (1984). The best separation line between oils sourced from predominantly waxy terrestrial organic matter and those oils generated from marine kerogen is also shown in **Figure III-5**. Oils within a basin which plot within 1 per mil (‰) unit are often genetically related, while oils with more than 1 or 2 ‰ difference may have been derived from different source rocks. The canonical variable (CV) of Sofer (1984) is essentially a measure of the perpendicular distance of a sample to the best separation line; negative values imply a nonwaxy marine origin while positive values suggest a lacustrine or nonmarine organic source. Biodegradation and thermal maturity differences usually only have a small effect on the carbon isotopic composition of oils which share a common source (<1 ‰).

Most of the Carnarvon oils cluster about -27‰ ± 0.5‰ for the saturate hydrocarbons, suggesting either a common or very similar source facies. However, many of the Dampier oils plot above Sofer's best separation line which implies some source differences. The Browse Basin oil from North Scott Reef-1 (AU279) plots with the Dampier oils. Rough Range Exmouth oils and the West Tryal Rocks Field oils (AU120-121) are significantly heavier most likely due to different sources. Many Perth oils have rather negative carbon isotopic compositions, plotting in the terrigenous field consistent with the waxy nature of some of these oils. Other Perth oils are isotopically much heavier suggesting multiple sources within the Perth basin. Bintuni oils from Indonesia are also very positive, reflecting their Miocene marine source.

As with isoprenoid ratios, the Petrel and Vulcan sub-basin oils are distinct with respect to carbon isotopes, although the differences are small. The exception is the Petrel condensate sample (AU353) which is more than 3 ‰ heavier than the other Petrel sub-basin oils. Even extreme differences in thermal maturity cannot account for these differences; another source component for the Petrel condensate must be invoked. Canning Basin oils have a wide range of isotopic composition suggesting multiple sources. Oils from three different wells in the Blina Field (AU140, 141, 329) are all within 0.1‰, indicating the analytical precision necessary to make subtle interpretations using carbon isotopes.

Figure III-6 is a cross plot of Pr/Ph from whole crude gas chromatography versus the CV from carbon isotopic analyses. A multiple parameter approach is necessary to confidently distinguish oils from different sources. Many oil groups begin to separate more clearly including oils from the Dampier and Barrow sub-basins. As biomarker parameters are added, and with the incorporation of multivariate statistical methods to handle all of the key geochemical variables, a greater understanding of oil family groupings will emerge.

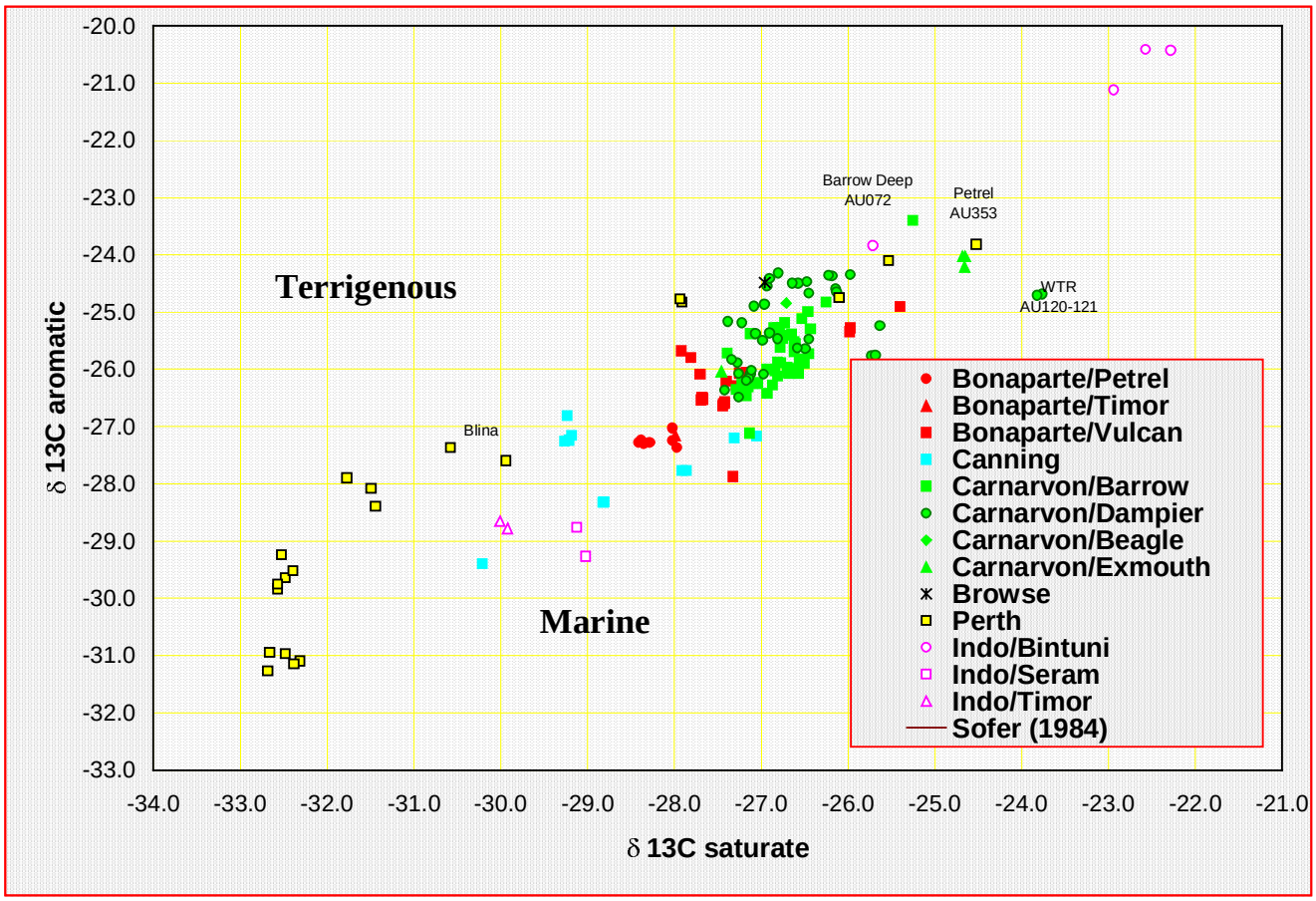


Figure III-5. Stable carbon isotope composition.

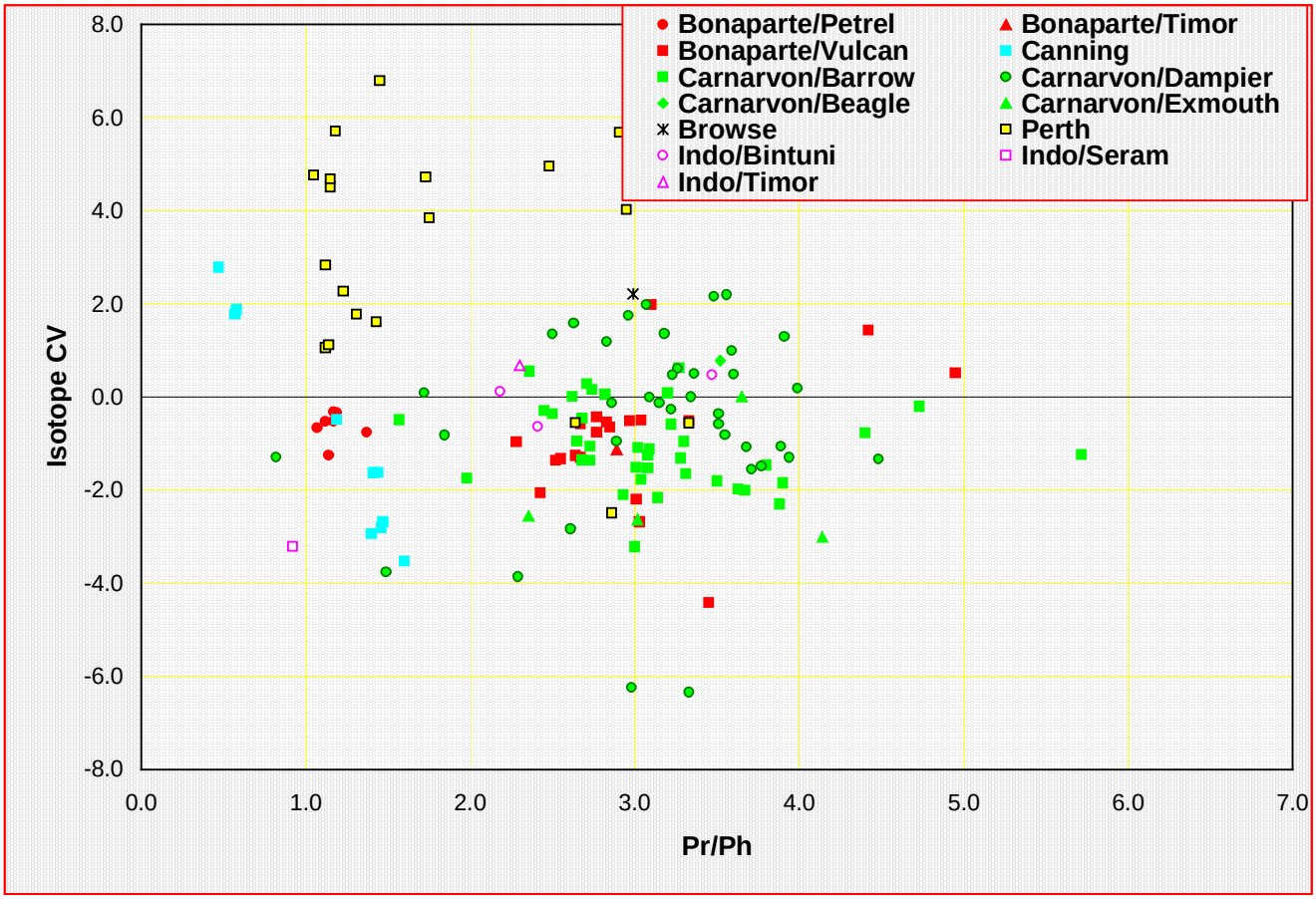


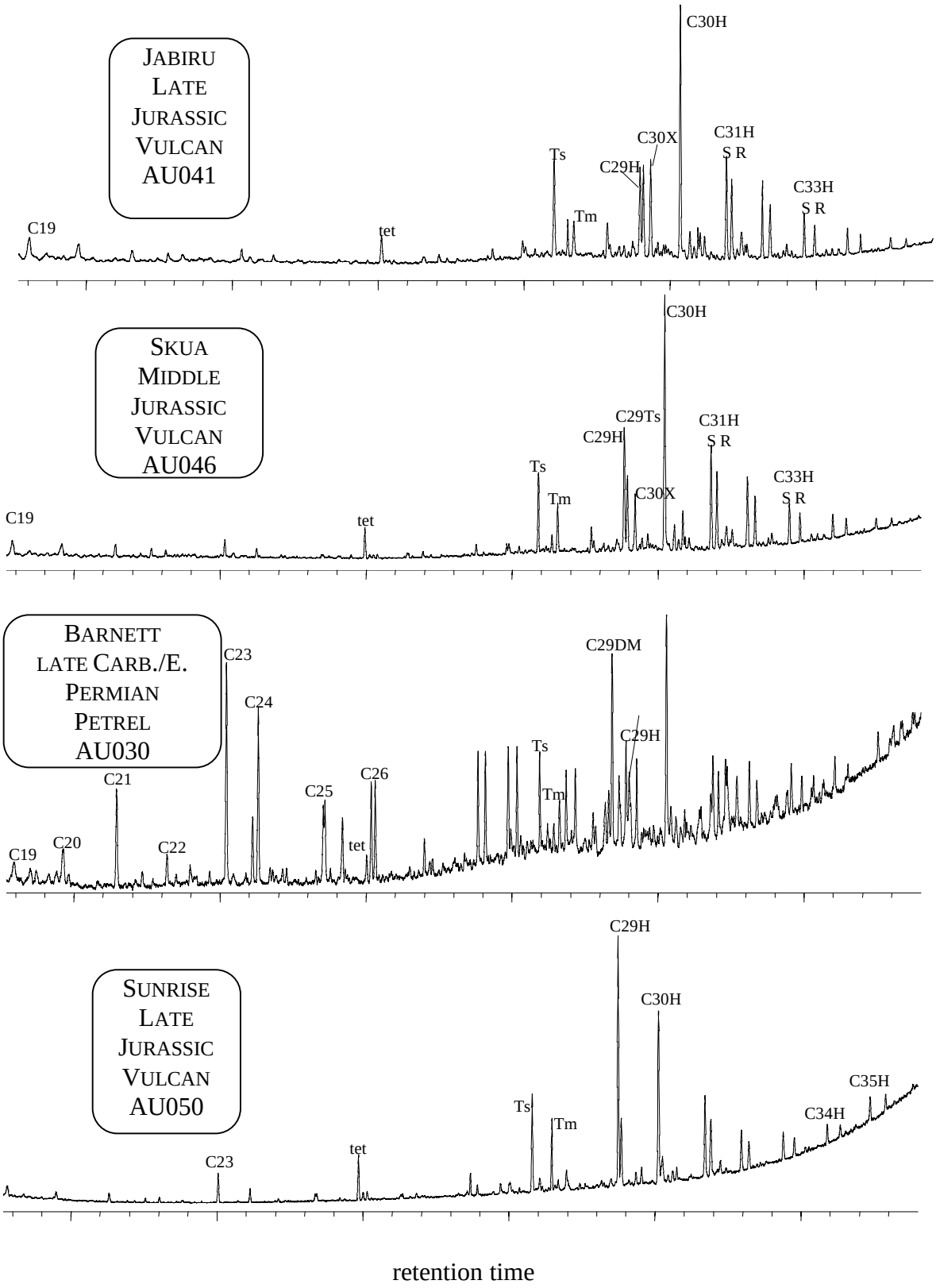
Figure III-6. Carbon isotopic canonical variable versus Pr/Ph.

Biomarkers

Biomarkers, or geochemical fossils, are defined as organic compounds found in sedimentary rocks or oils in which a sufficient part of the carbon skeleton has been preserved. These compounds, called terpanes and steranes, can be correlated with the original biochemical precursor after having undergone accumulation, diagenesis, and even catagenesis (i.e., oil generation). Thus, biomarkers are indicators of depositional environments in the same manner that physical remains of organisms can describe depositional systems. Biomarkers can also be used as thermal maturity indicators. Good reviews of biomarkers and their applications in petroleum geochemistry can be found in Mackenzie (1984) and Peters and Moldowan (1993). Examples of oil terpane (m/z = 191 mass chromatograms) and sterane (m/z = 217 mass chromatograms) biomarker distributions are given in **Figures III-7a, b** through **III-10a, b** for the Bonaparte, Canning, Carnarvon, and Perth Basins, respectively. The identity of these biomarkers and a table listing their concentrations are given in **Appendix B**.

Four terpane biomarker distributions from the Bonaparte Basin are shown in **Figure III-7a**. The Vulcan sub-basin examples, Jabiru and Skua, have overall similarities with relatively high terrigenous markers such as C19/C23 tricyclic ratios, a prominent tetracyclic component (tet), and abundant diahopanes (e.g., C30X) typical of shale/claystone source rocks. The principal difference between Jabiru and Skua can be attributed to differences in thermal maturity. The thermally more stable Ts compounds relative to Tm (both the C27 and C29 terpanes), as well as the more stable C30X diahopane relative to hopane (C30H), for example, all indicate a higher thermal history for the Jabiru oil.

The Barnett oil terpanes from the Petrel sub-basin are quite different than the Vulcan oils, consistent with the gas chromatographic and carbon isotopic analyses. One important difference is the presence of two unknown tricyclic components which elute just prior to C24 and between the C25 and C26 doublets. These compounds may be key source indicators for this petroleum system. Another important class of compounds present in the Barnett oil are the demethylated hopanes (e.g., labeled C29DM in **Figure III-7a** and including the complete suite of C27 - C34 demethylated hopanes visible on the m/z = 177 mass chromatogram). These compounds are thought to form as a result of the action of extensive aerobic biodegradation of reservoired oil at relatively shallow depths. However, the presence of a complete suite of normal paraffins in this oil, compounds which are most easily biodegraded and should, therefore, be absent, strongly suggests a paleobiodegradation event followed by further charging of the reservoir with ‘fresh’ non degraded oil containing abundant *n*-paraffins. Either the reservoir was subsequently buried deeper where temperatures became too extreme for aerobic bacteria (ca. 70-80° C), or the oxygen supply from the circulating ground waters ceased for some reason. The subsequent ‘fresh’ oil could have been generated from continuous generation of the same source or, alternatively, from another source facies.



retention time

Figure III-7a. Terpane Mass Chromatograms (m/z = 191): Bonaparte Basin.

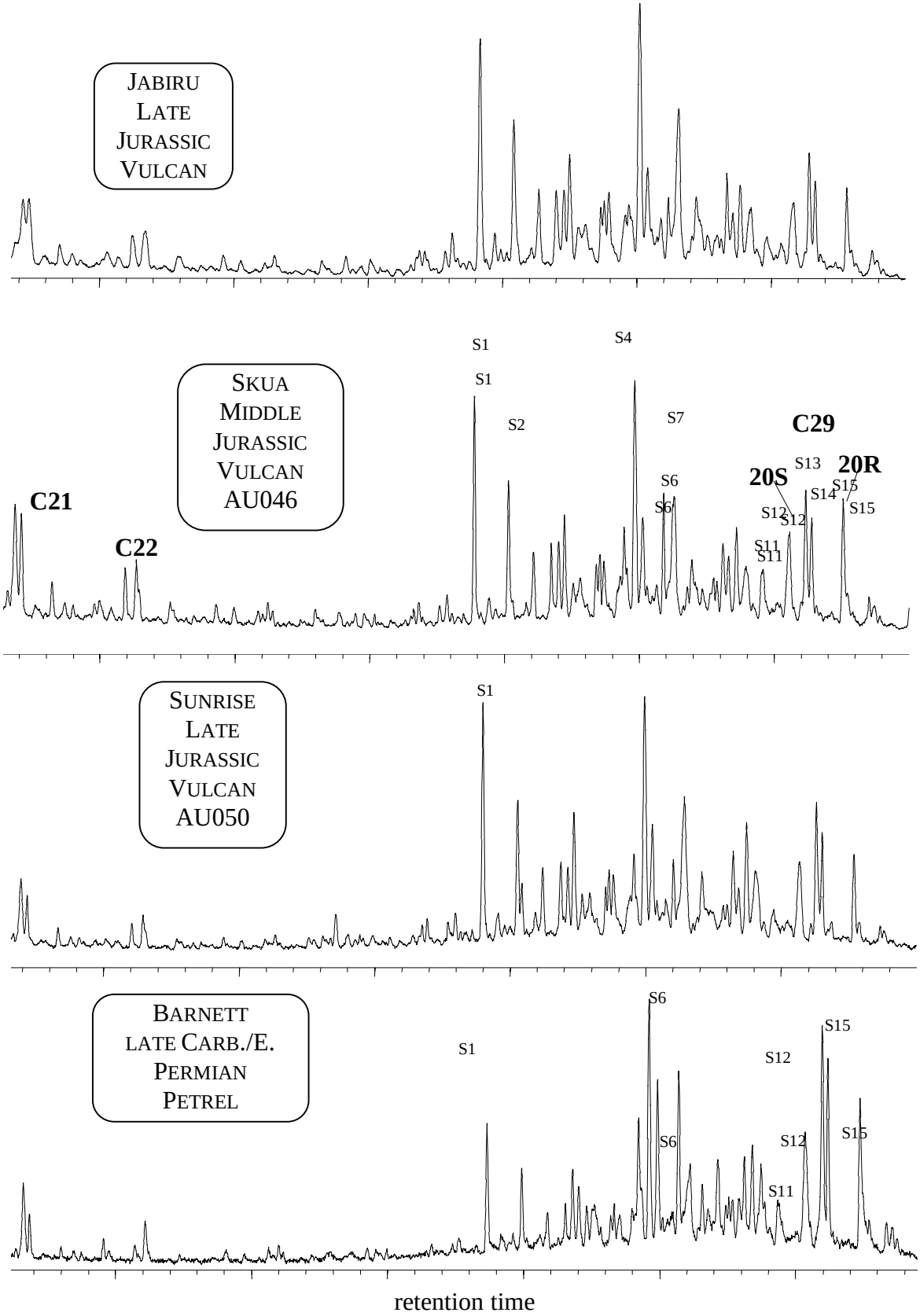


Figure III-7b. Sterane Mass Chromatograms (m/z = 217): Bonaparte Basin.

The Vulcan Sunrise oil terpanes, also illustrated in **Figure III-7a**, present clear evidence as being derived from a carbonate source rock. These characteristic carbonate markers include high norhopane to hopane (C29H/C30H) and C35/C34 ratios.

Sterane mass chromatograms for the same four Bonaparte oils are illustrated in **Figure III-7b**. The C27, C28, and C29 α,β,β isomers are used to determine the relative distribution of these three regular steranes which are useful source indicators. (These three compounds are actually measured using the m/z = 218 mass chromatogram and are labeled S5B, S10B, and S14B for the C27, C28, and C29 components, respectively, in **Appendix B**). The C29 20S/20R ratio (S12/S15) can be used to distinguish low from moderately mature oils; peak height measurements of these two compounds often give more accurate ratios than peak areas due to near coelution by non sterane components.

Another useful sterane ratio is the relative abundance of rearranged to regular steranes. The C27 rearranged (S1) to the 20R α,α,α C27 regular sterane (S6) is a convenient ratio to measure (using the m/z = 217 mass chromatogram; S4 also contains a C29 rearranged sterane). The S1/S6 ratio is maturity dependent (increases with increasing thermal maturity; e.g., Zumberge, 1987a), but is often also a function of source rock lithology. Since the rearrangement reaction progresses faster under acid catalyzed conditions, the rearranged sterane is usually larger than the regular sterane (S1/S6>1) in clastic sources containing abundant clay and silica (at moderate thermal maturities). In many carbonate source rocks, which may lack sufficient silica, the rearranged steranes are much less abundant (S1/S6<1) at equivalent thermal maturities.

Again, the Jabiru/Skua oils are similar except for the much higher S1/S6 ratio in Jabiru, consistent with higher levels of thermal maturity. The C29 S/R maturity ratio is also lower in the Skua oil. The Barnett steranes are not all that different from Vulcan oils, except for lower amounts of C28 steranes (S11) , often observed in Paleozoic as opposed to Mesozoic-sourced oils. The Sunrise steranes confirm the carbonate/marl source nature with a relatively low S1/S6 value.

Canning Basin terpane biomarkers are shown in **Figure III-8a**. The Carboniferous-reservoired West Terrace oil terpanes are typical of a marine shale source. Although smaller in abundance, the same unknown tricyclic markers present in Petrel sub-basin oils (Barnett and Turtle) are observed in oils from West Terrace, Sundown, Meda, and Lloyd fields. However, the Canning Carboniferous oils do not contain demethylated hopanes, implying a lack of paleobiodegradation. Ordovician Dodonea terpanes are different than West Terrace terpanes in that the unknown tricyclics are absent, diahopanes are low, and the norhopane to hopane ratio is larger, all indicating a different source. Devonian Blina oil terpanes indicate yet another source in the Canning Basin. The relatively large gammacerane (GA) component implies more of a restricted, perhaps hypersaline source environment (or at least significant water column stratification according to Sinninghe Damste *et al.*, 1995). Regarding Canning Basin steranes (**Figure III-8b**), differences are largely due to variations in the relative abundance of diasteranes (rearranged steranes): West Terrace > Dodonea > Blina.

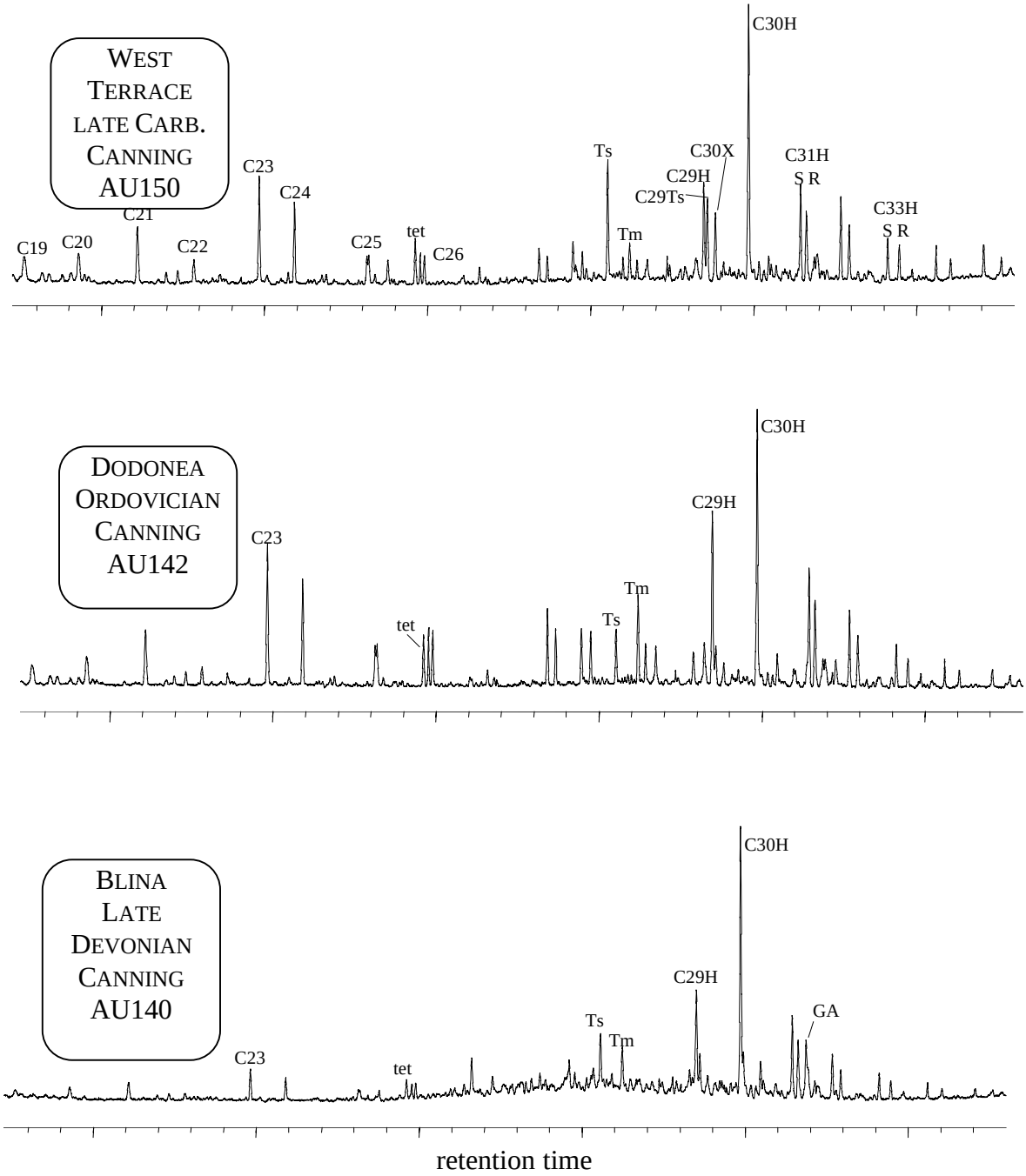


Figure III-8a. Terpane Mass Chromatograms (m/z = 191): Canning Basin.

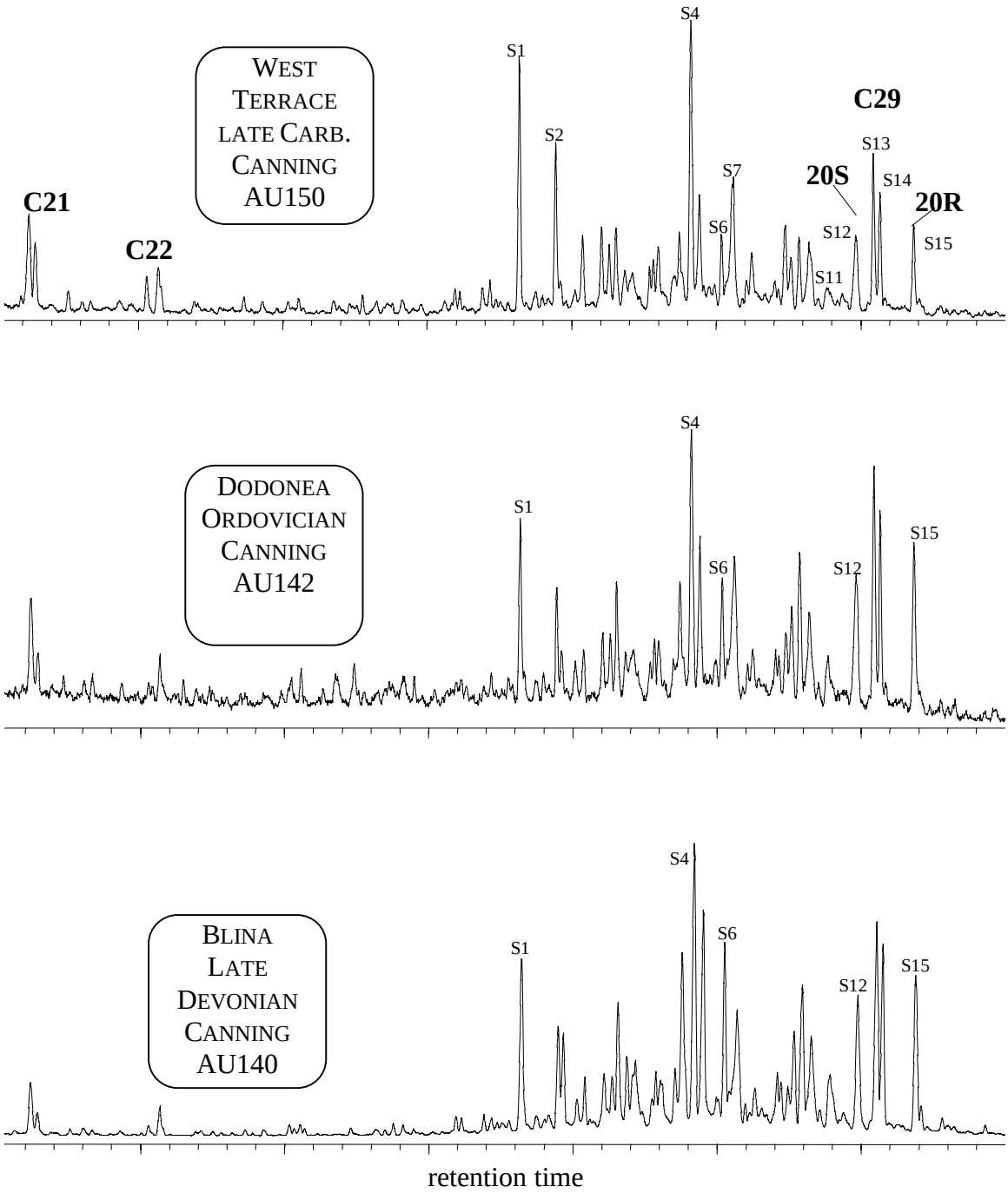


Figure III-8b. Sterane mass chromatograms (m/z=217): Canning Basin.

Five representative terpane mass chromatograms from the Carnarvon Basin are illustrated in **Figure III-9a**. Barrow Island and Talisman oils are not unlike Bonaparte Vulcan oils in that C19 and tetracyclic compounds are abundant relative to C23 as are the diahopanes. Goodwyn oils (Dampier sub-basin) contain even more terrestrial tricyclics (C19 and C20) with the addition of demethylated hopane. Abundant *n*-paraffins in this oil again suggest paleobiodegradation. Exmouth Rough Range oil contains very abundant C19 and C20 terrigenous terpanes with little of the marine C23 and C24 tricyclics. Leatherback oil also appears to have a major nonmarine component. In addition, this oil is of low thermal maturity with relatively abundant moretanes (e.g., C29M) and a low sterane C29 S/R ratio (S12/S15; **Figure III-9b**) suggestive of a vitrinite reflectance equivalent (VRE) of about 0.6 %. Rough Range steranes indicate a higher level of maturity, VRE = ~ 0.7 %, well within the oil window.

Perth Basin biomarker distributions are shown in **Figures III-10a** and **III-10b**. North Erregulla oil in the E. Triassic appears most marine while Gage Roads was generated from source rocks containing primarily nonmarine organic matter. Permian Whicher Range and E. Jurassic Walyering oils are somewhat intermediate. These general observations are based upon the relative abundance of tricyclic terpanes (e.g., C19/C23 ratios) and regular steranes (e.g., C27/C29 ratios). Gage Roads oil appears to be the least thermally mature based upon the low C29 S/R ratio.

Figures III-11, **III-12**, and **III-13** are examples of various biomarker ratio cross plots indicating source differences and similarities among the west Australian oils. Carnarvon Dampier and Barrow oils can generally be distinguished in **Figure III-11** with most of the Dampier oils having higher C24 tetracyclic (tet) to C23 tricyclic ratios. Bonaparte Vulcan and Petrel oils are again different since the former have much higher C19/C23 and tet/C23 ratios indicative of a larger terrigenous component. Most Canning and many Perth oils have low values for these ratios. In **Figure III-12**, which plots norhopane/hopane (C29/H) against C30 diahopane/H, shows the low diahopane and high C29 content of carbonate-sourced oils including the Indonesia Seram oils and the Vulcan Sunrise oil. However, the diahopane/H ratio is also highly dependent upon thermal maturity; source relationships can become obscured using this parameter if significant differences in maturity are evident. **Figure III-13** highlights the oils which contain the paleobiodegradation marker, demethylated hopane (DM). In the Carnarvon Basin, many Dampier and Barrow oils have demethylated hopanes, although the Dampier oils generally have a greater DM/Hopane ratio than Barrow oils to the south. Petrel oils contain abundant demethylated hopanes while Vulcan oils do not. Canning and Perth oils contain little, if any, demethylated hopanes.

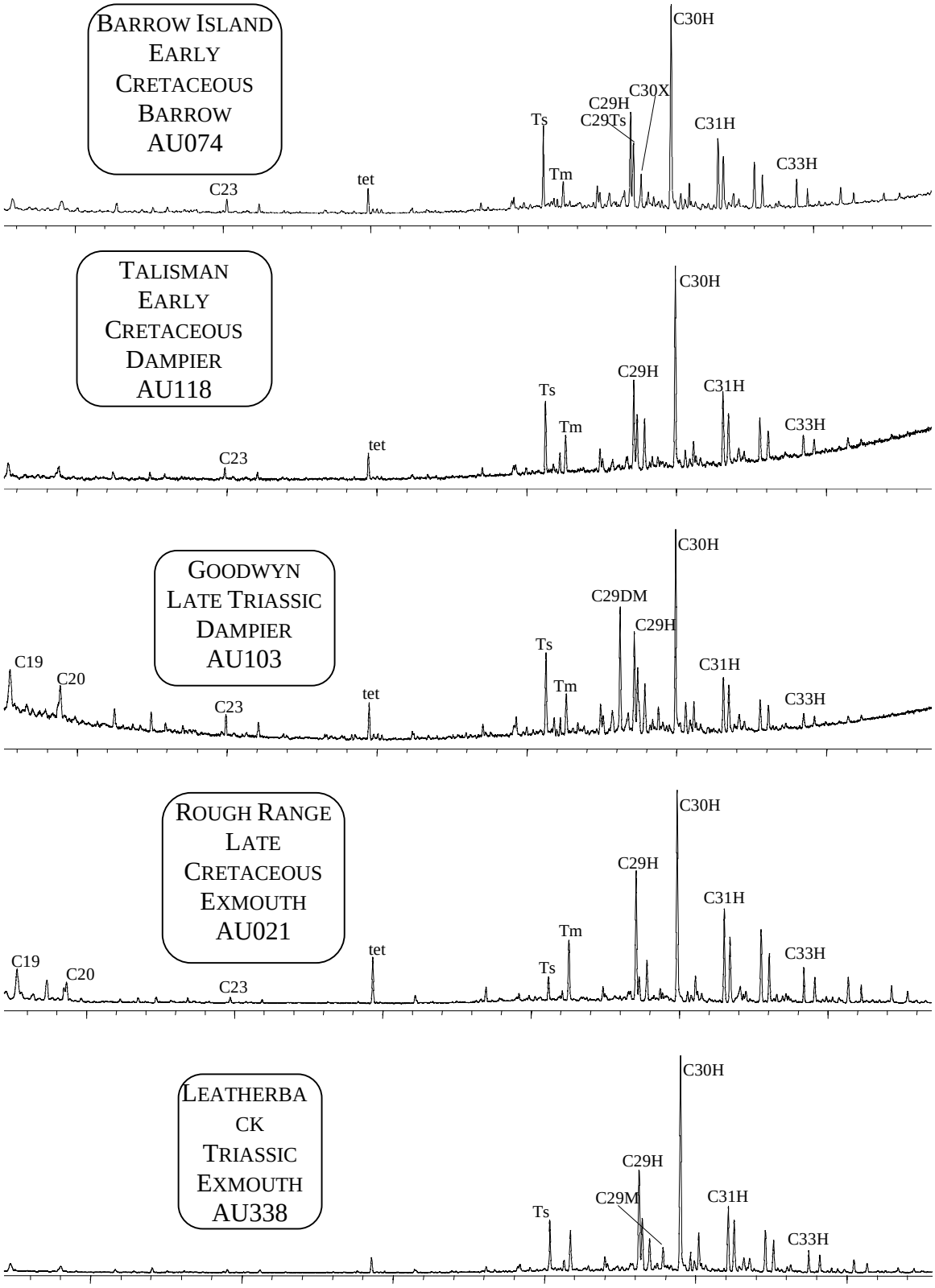


Figure III-9a. Terpane Mass Chromatograms (m/z = 191): Carnarvon Basin.

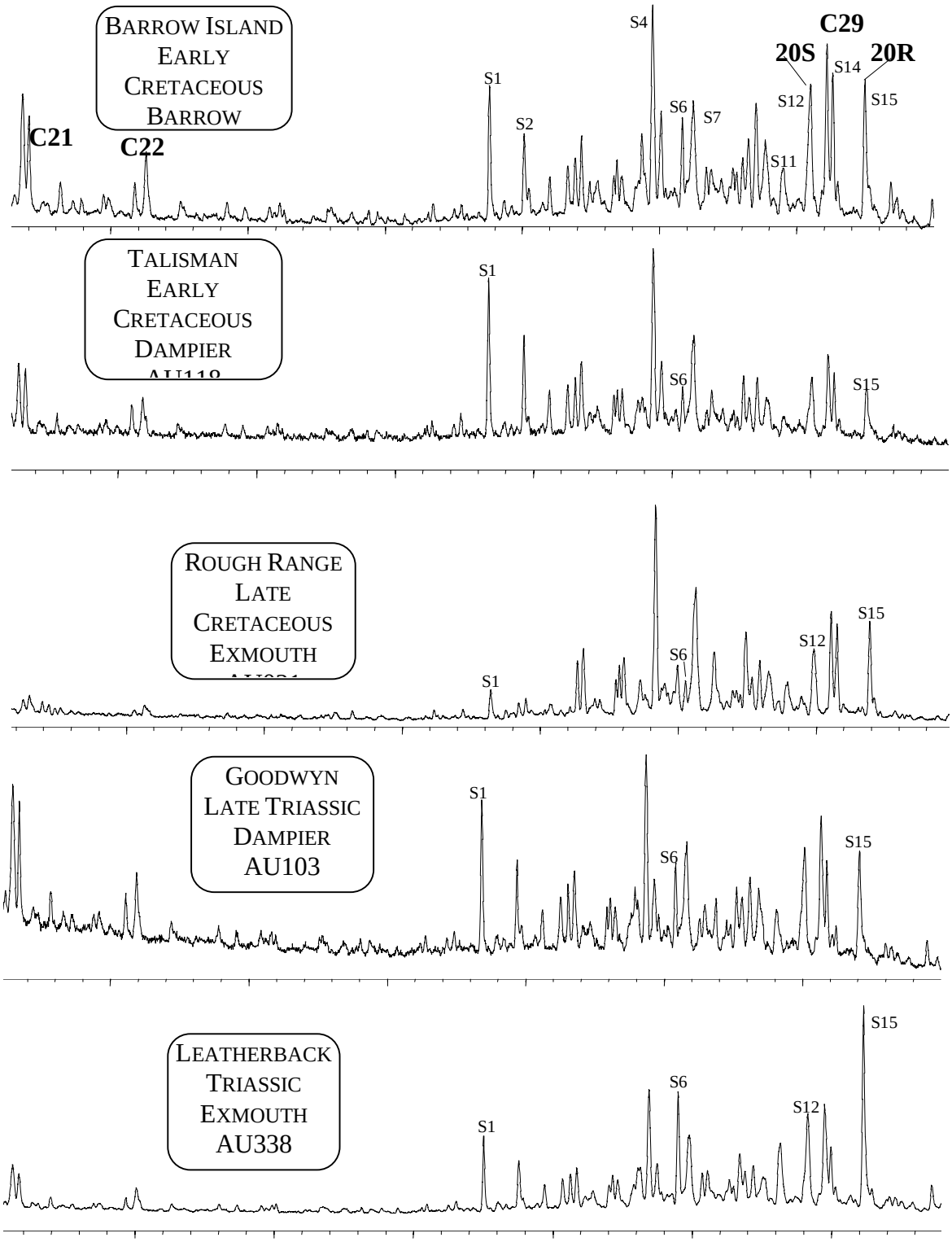


Figure III-9b. Sterane Mass Chromatograms (m/z = 217): Carnarvon Basin.

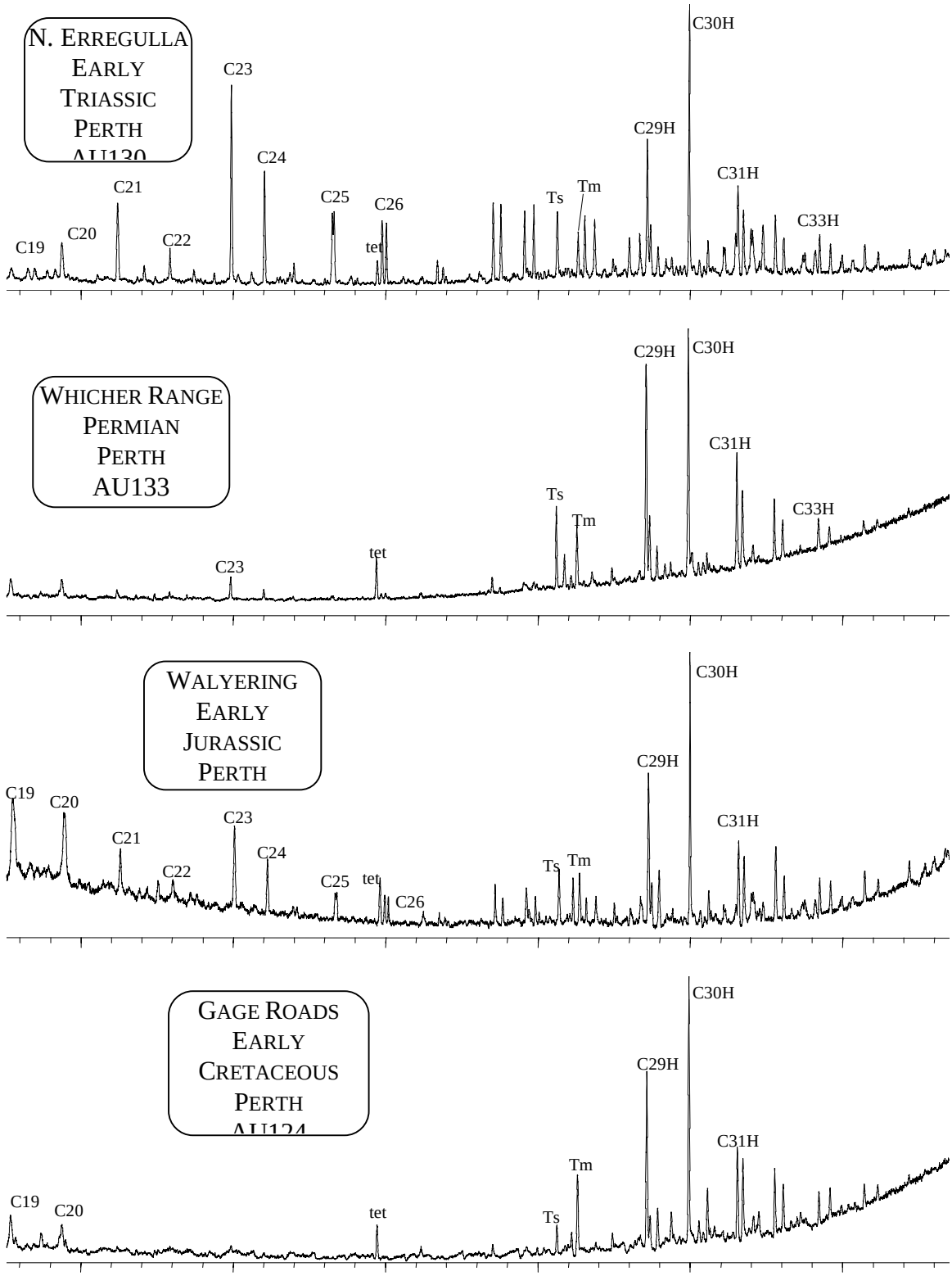
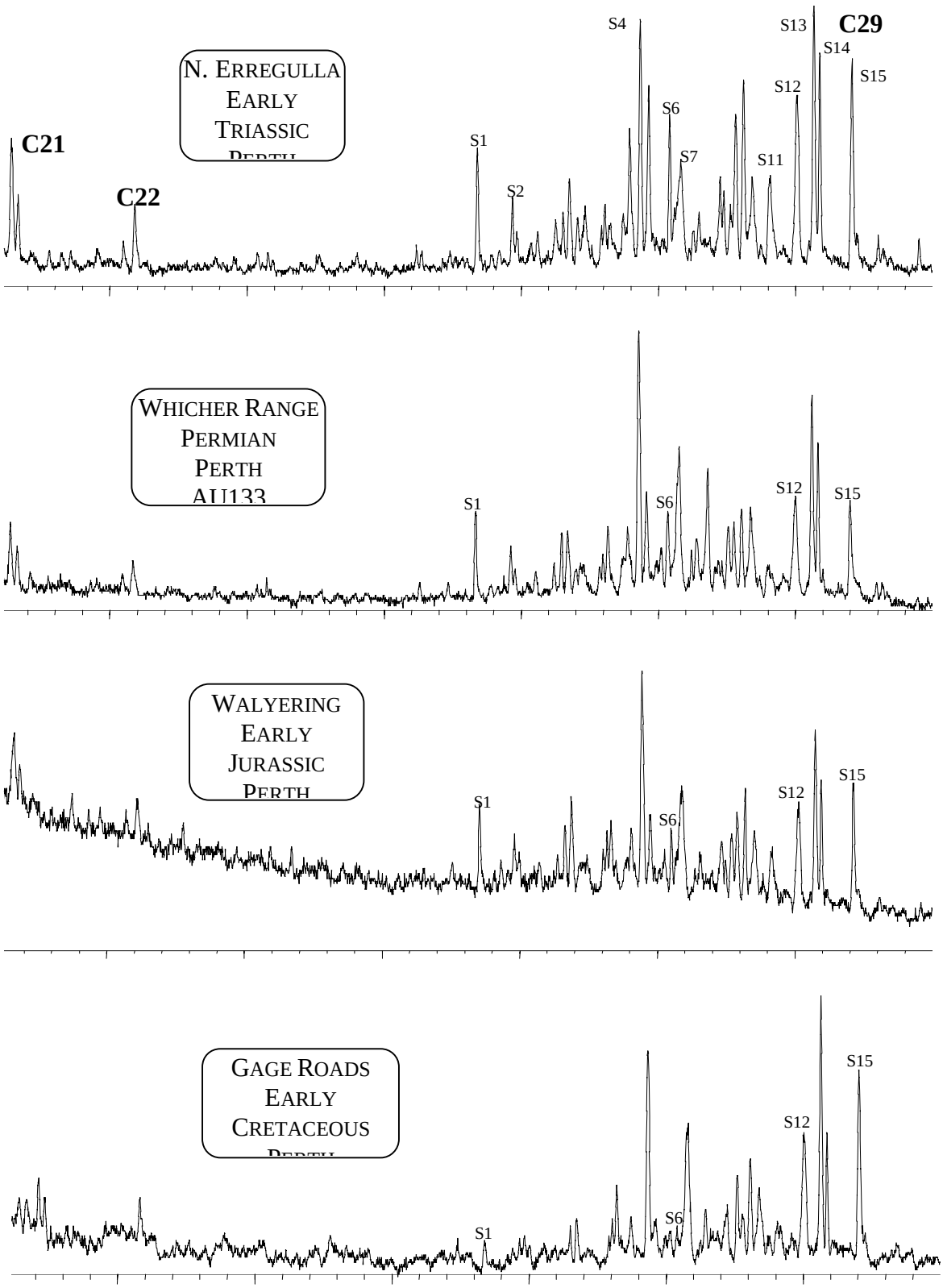


Figure III-10a. Terpane Mass Chromatograms (m/z = 191): Perth Basin.



retention time

Figure III-10b. Sterane Mass Chromatograms (m/z = 217): Perth Basin.

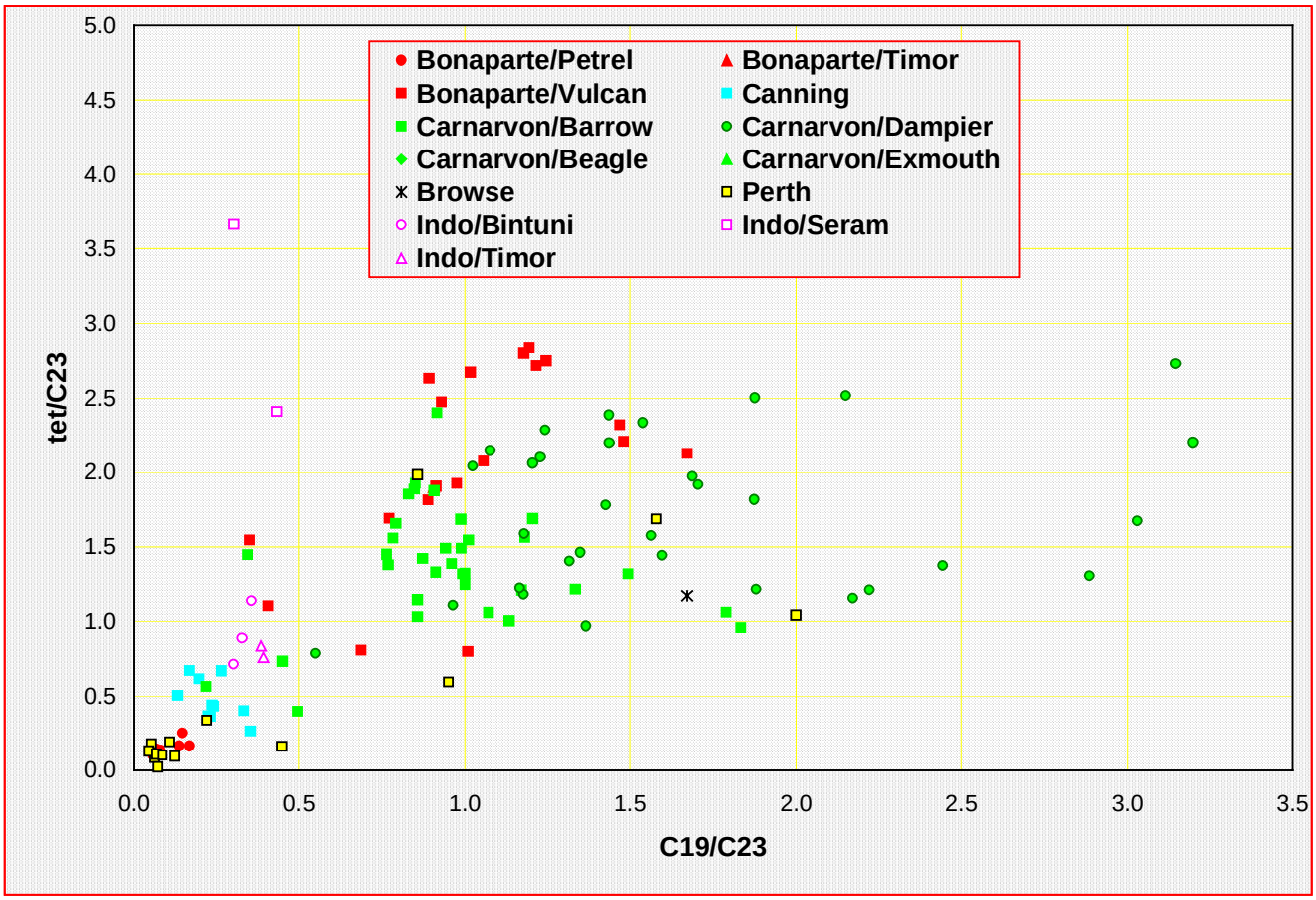


Figure III-11. Tricyclic terpane C19/C23 versus Tetracyclic Terpane/C23.

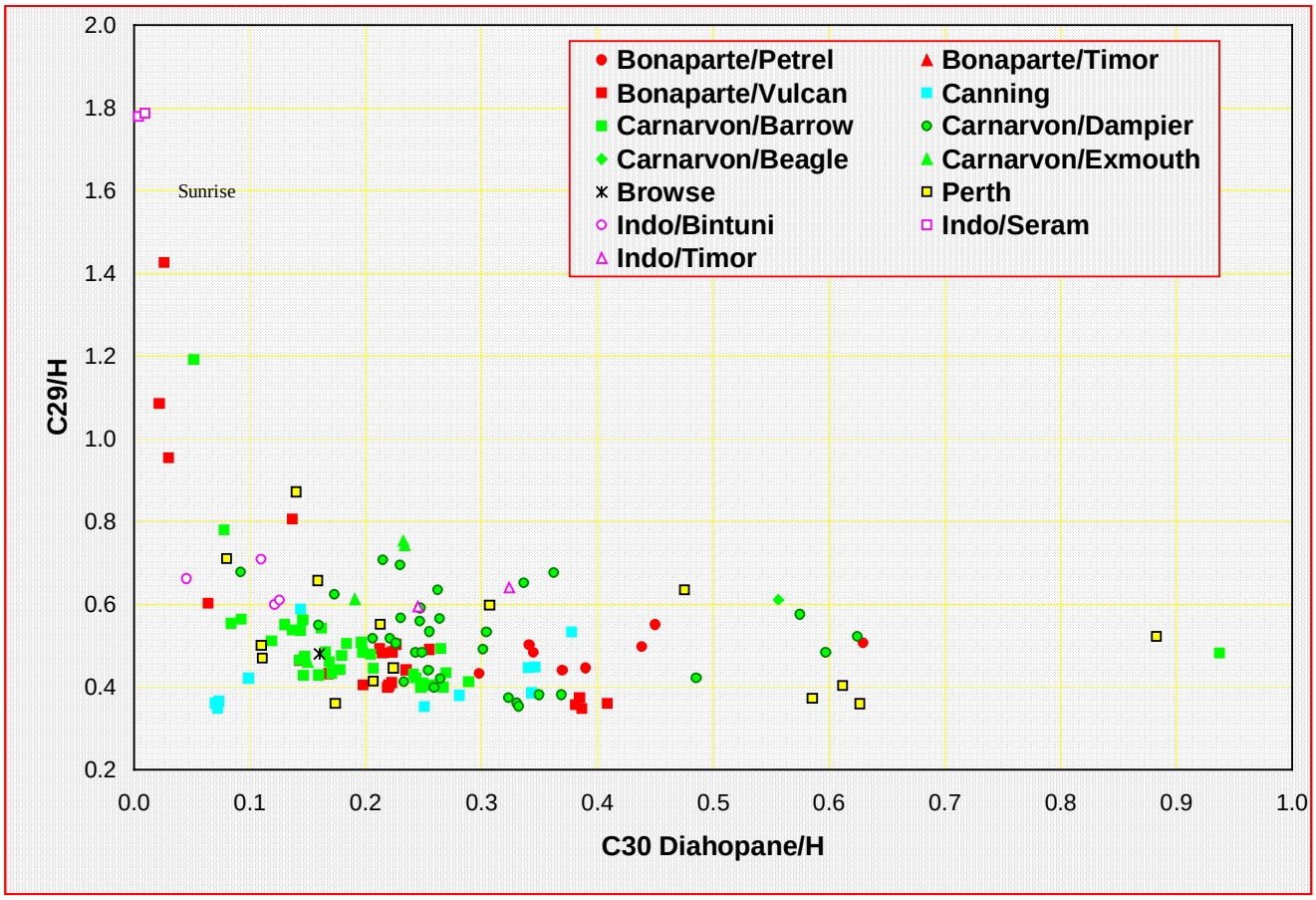


Figure III-12. C29/C30 hopanes versus Diahopane/Hopane.

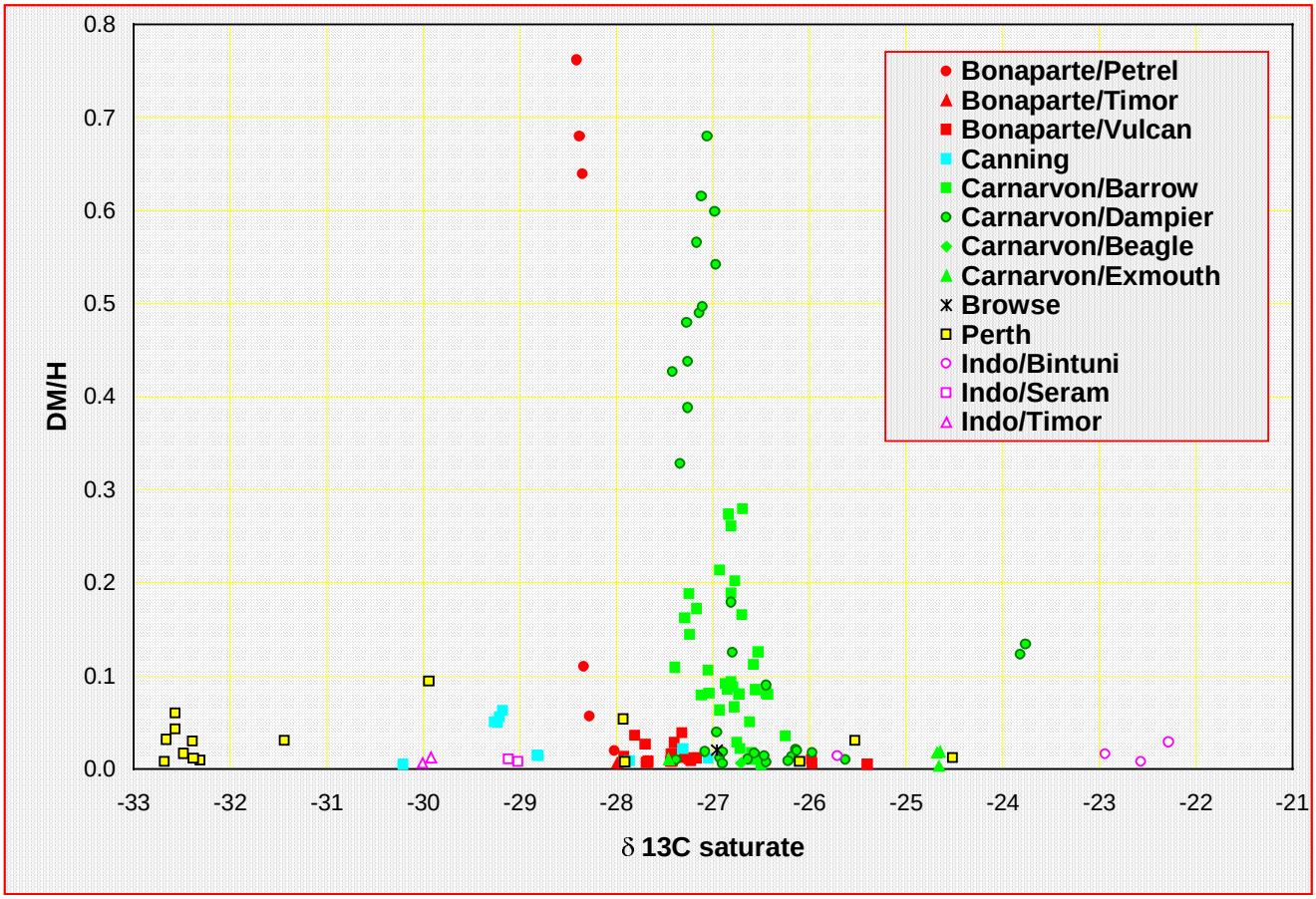


Figure III-13. Carbon isotope composition versus demethylated hopane.

Cluster and Principal Component Analysis

Multivariate statistical analyses can be used to more clearly distinguish both source rock depositional environments and genetically related oil families using all of the pertinent geochemical variables (Zumberge, 1987b). The two statistical treatments used in the present study are termed principal component analysis (PCA) and cluster analysis and were performed using a personal computer and a series of computer programs from Infometrix, Seattle, WA. (Pirouette™). Briefly, in PCA new independent variables are created (i.e., principal components) that are linear combinations of the original variables (i.e., geochemical parameters). The primary objective of PCA is to reduce the dimensionality of the data to a few important components that best explain the variation in the data. Prior to PCA, the original geochemical variables are autoscaled (the mean value for each variable is subtracted and divided by the standard deviation) so that, say, carbon isotope values (e.g., -28 ‰) can be compared in a meaningful way to sterane/terpane ratios, for example. Oil samples can be plotted in principal component space, PC1 versus PC2, just like any other x-y plot. This is called a Scores plot. Also, the geochemical variables responsible for the PC axes can also be viewed as a Loadings plot. Cluster analysis is an ancillary technique to PCA whereby a distance matrix is created from the scaled data; the distance between any two samples is a measure of their similarity. (This distance is similar to a linear correlation coefficient; perfect correlation would have a value of 1.0 while poor correlation would have values <0.5.) The dendrogram is the output of a cluster analysis and shows groupings or clusters of related oils.

Oils from each basin are treated separately, with cluster analysis dendrograms and principal component plots constructed for each of the four major basin under consideration. Dendrogram clusters and PCA groupings represent separate oil families or systems which share a common source. Most of the geochemical variables chosen for statistical treatment are dependent more upon source rather than thermal maturity. Maturity trends within oil families determined by cluster and principal component analyses are then plotted based upon thermally sensitive C27 and C29 terpane ratios (Ts/Tm).

BONAPARTE BASIN

The dendrogram shown in **Figure III-14** and principal component plots given in **Figures III-15** and **III-16** are based on two gas chromatographic ratios, Pr/Ph and n-C27/C17, the carbon isotopic composition of both the saturate and aromatic hydrocarbon fractions, and nine terpane and five sterane biomarker ratios. These variables are plotted on the principal component figures in order to aid in the interpretation of the geochemical variables responsible for the oil groupings. Color codes, representing different oil families, are repeated in the dendrogram as well as the principal component plots. The correlation coefficient scale across the top of the dendrograms aid in determining the oil families. Oils with very high correlations, such as the two Barnett oils from the same reservoir (**Figure III-14**; AU030 and 031;

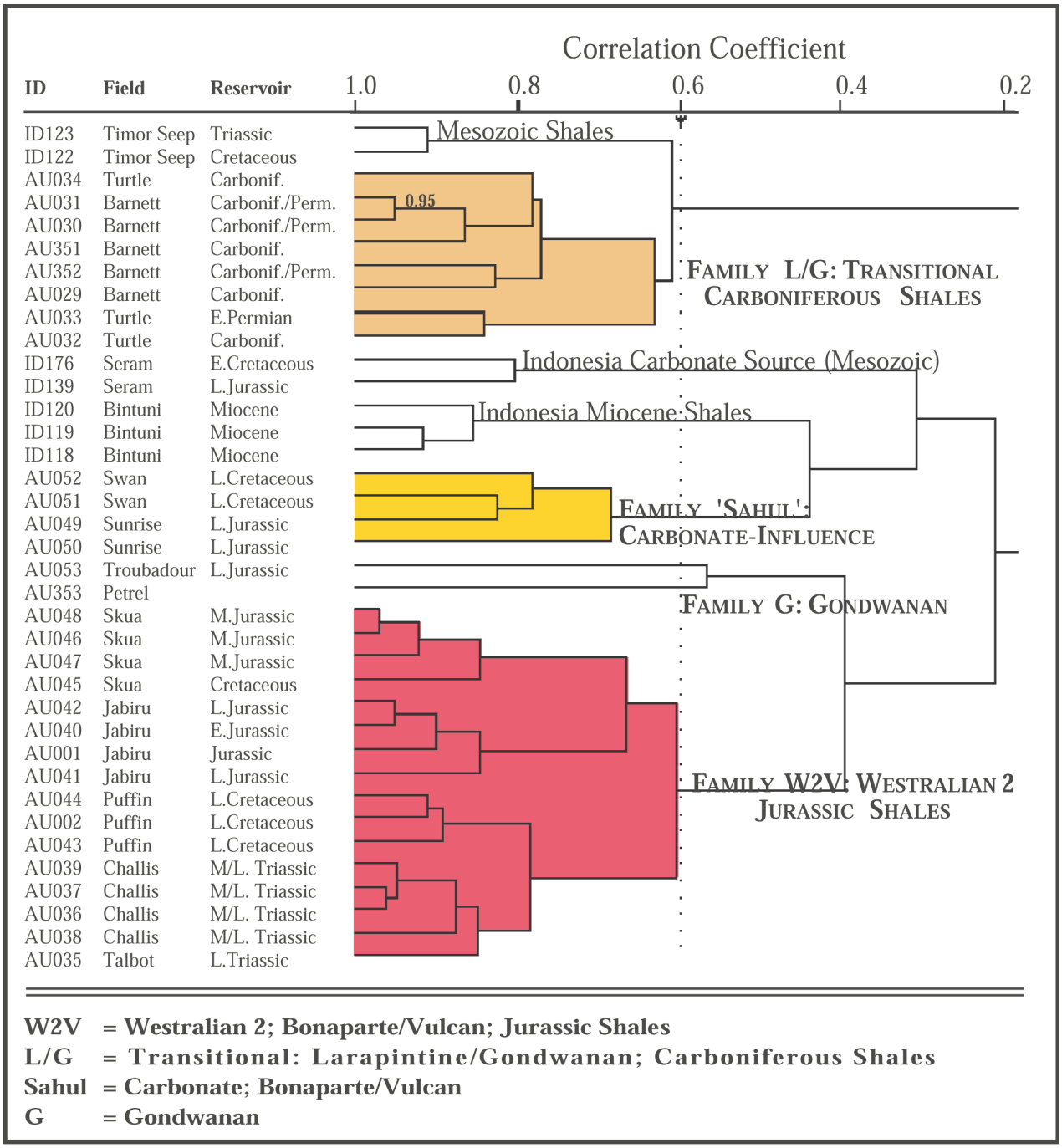


Figure III-14. Cluster Analysis Dendrogram: Bonaparte Basin.

0.95 correlation), help determine analytical and reservoir variations while larger variations among fields within the same family suggest slight source facies variations or differences caused by thermal maturity. As will be seen later, the rather low 0.6 correlation defining the W2V Family is due primarily to rather wide differences in source rock maturity.

Three major petroleum families are evident in the Bonaparte Basin. Oils of the Petrel sub-basin from the Turtle and Barnett fields are distinctly different from Vulcan sub-basin oils of the Jabiru, Challis, Puffin, Skua, and Talbot fields. These families are labeled L/G: Transitional Carboniferous Shales and W2V: Westralian 2 Jurassic Shales on the dendrogram and PCA plots. The reason for assigning the different oil families to the petroleum systems discussed in Chapter II will be further explored in the Integrated Discussion of Chapter IV. Members of the third oil family ('Sahul') are from the Sunrise-1 well and perhaps the Swan tests, although the later may have been contaminated by drilling fluids.

The PCA plots in **Figures III-15** (PC1 versus PC2) and **III-16** (PC1 versus PC3) also indicate which geochemical variables are responsible for the separations of the various oil families. Petrel sub-basin Family L/G contain relatively high values for steranes/hopanes (S/H), C24/C23 tricyclic terpane ratio, and bisnorhopane (C28/H) while Vulcan Family W2V has higher values of terrigenous markers such as C19/C23 tricyclic terpane ratio, %C29 sterane and are more waxy (higher n-C27/n-C17 ratio). As expected, the carbonate/marl-sourced Sunrise oil has a high norhopane/hopane (C29/H) ratio and low diasteranes (S1/S6) and diahopanes (X/H).

The Indonesian oils are also shown in **Figures III-14, III-15**, and **III-16**. No close correlations to Bonaparte oils were observed. The isotopically very positive (**Figure III-16**) Bintuni samples contain the Tertiary marker oleanane and were likely generated from Miocene shales. As mentioned before, the Seram oils are sourced from Mesozoic carbonates while the Timor seeps are isotopically light, probably generated from a Mesozoic shale.

The Petrel oil (AU353) is isotopically very heavy and plots as a 'vagrant' oil on the PCA plots as does the Troubadour sample (AU053) although it may be related somewhat to the Sunrise 'Sahul' oil (**Figure III-16**) which is located close by.

Family Summary Table and Thermal Maturity

Summary **Table III-2** lists the oil samples and field names within each family as determined by the various cluster and principal component analyses. In addition, the oils are listed in order of increasing thermal maturity based on C27 terpane Ts/Tm ratios within each sub family. The principal component values, carbon isotope composition, and other maturity parameters (C29 Ts/Tm or 29D/H and diasteranes/regular steranes S1/S6) are also listed for each oil. DM/H is a measure of the relative amount of demethylated hopane and indicates severe paleobiodegradation; as mentioned previously,

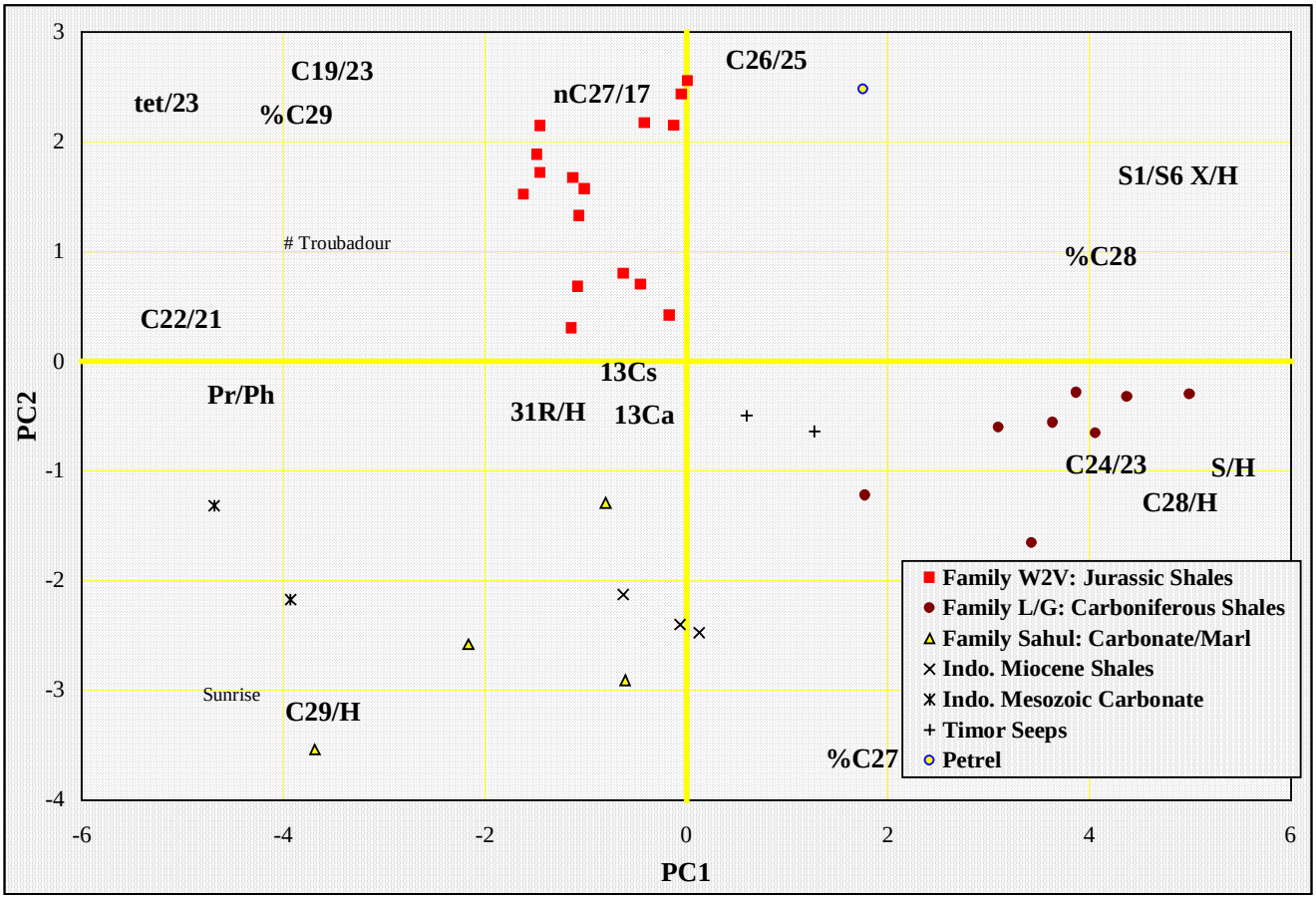


Figure III-15. Principle component scores and loadings plot: Bonaparte basin.

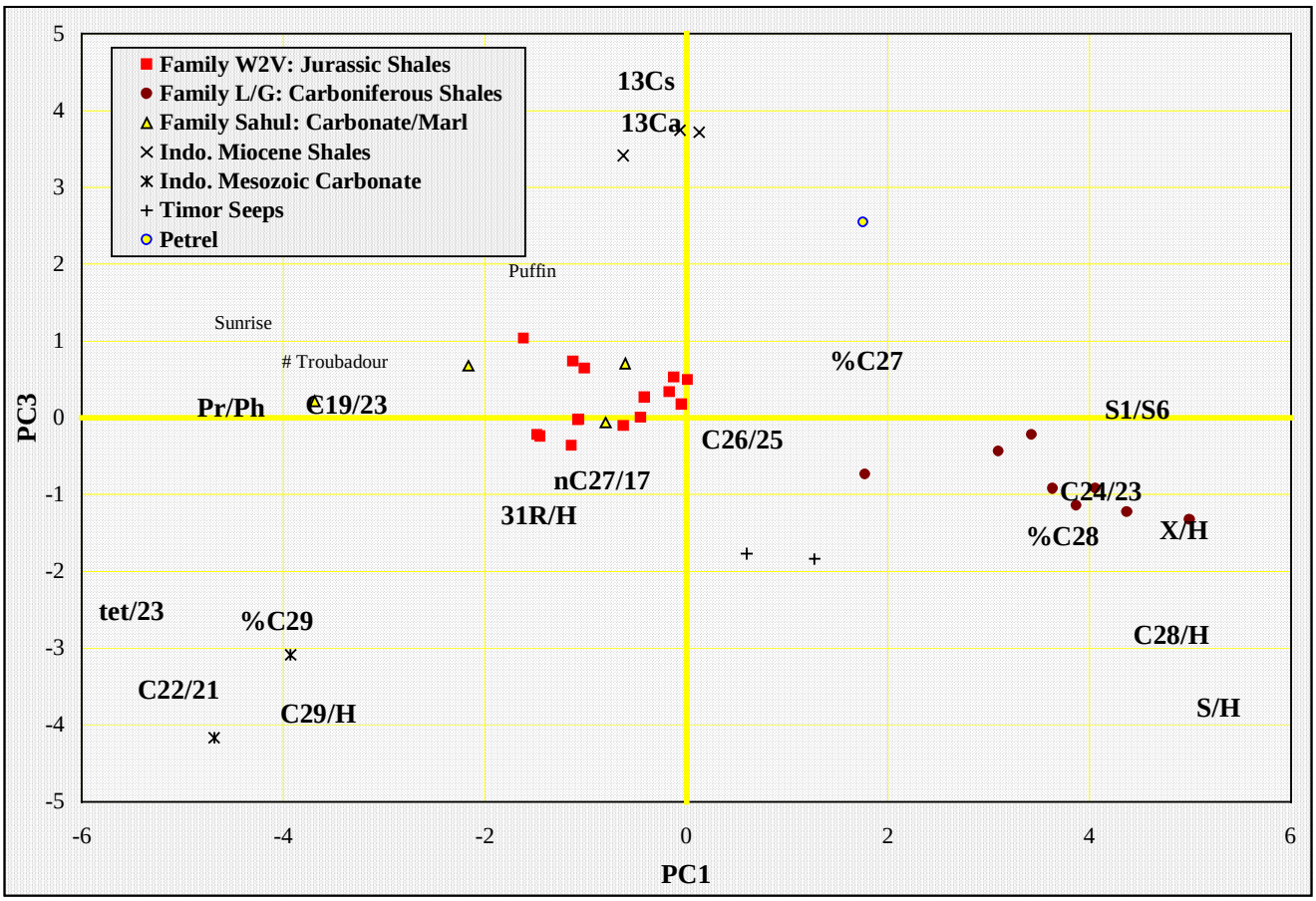


Figure III-16. Principal component scores and loadings: PC1 versus PC3.

Table III-2. Bonaparte Oil Families; Listed in Order of Increasing Thermal Maturity.

	Field	Depth (m)	*PC 1*	*PC 2*	*PC 3*	13Cs	13Ca	S1/S6	Ts/Tm	29D/H	DM/H
Family W2V											
AU035	Talbot	1540	*-1.14*	*0.30*	*-0.36*	-27.99	-27.16	1.09	1.62	0.61	0.01
AU046	Skua	2381	*-0.45*	*0.70*	*0.00*	-27.44	-26.64	1.89	1.64	0.60	0.01
AU048	Skua	2339	*-0.62*	*0.80*	*-0.10*	-27.42	-26.60	1.93	1.68	0.62	0.01
AU047	Skua	2340	*-0.17*	*0.42*	*0.33*	-27.42	-26.57	1.92	1.71	0.59	0.01
AU045	Skua	2337	*-1.08*	*0.68*	*-0.03*	-27.43	-26.60	1.83	1.72	0.59	0.02
AU043	Puffin	2067	*-1.61*	*1.52*	*1.03*	-25.40	-24.91	1.26	1.83	0.62	0.00
AU002	Puffin	2035	*-1.01*	*1.57*	*0.65*	-25.97	-25.28	2.05	1.91	0.67	0.01
AU044	Puffin	2032	*-1.13*	*1.67*	*0.74*	-25.98	-25.35	1.80	1.92	0.66	0.01
AU039	Challis	1410	*-1.45*	*1.72*	*-0.23*	-27.68	-26.49	1.75	2.09	0.80	0.01
AU037	Challis	1387	*-1.45*	*2.15*	*-0.24*	-27.69	-26.54	1.91	2.13	0.80	0.01
AU038	Challis	1380	*-1.07*	*1.33*	*-0.02*	-27.67	-26.51	1.87	2.17	0.68	0.01
AU036	Challis	1404	*-1.48*	*1.88*	*-0.22*	-27.67	-26.53	1.74	2.19	0.80	0.01
AU001	Jabiru		*-0.05*	*2.44*	*0.17*	-27.29	-26.29	4.37	2.76	0.94	0.01
AU041	Jabiru	1780	*-0.41*	*2.17*	*0.27*	-27.25	-26.07	3.80	2.80	1.03	0.01
AU040	Jabiru	1628	*-0.12*	*2.15*	*0.53*	-27.23	-26.08	3.90	2.87	1.01	0.01
AU042	Jabiru	1694	*0.01*	*2.56*	*0.49*	-27.17	-26.06	3.98	3.00	0.98	0.01
Family L/G											
AU032	Turtle	1621	*5.00*	*-0.30*	*-1.33*	-28.02	-27.25	3.20	1.49	**0.50**	2.03
AU033	Turtle	927	*3.87*	*-0.29*	*-1.14*	-27.97	-27.37	2.96	1.58	**0.55**	1.53
AU030	Barnett	1497	*4.06*	*-0.66*	*-0.92*	-28.41	-27.28	3.50	1.93	**0.60**	0.76
AU031	Barnett	1507	*3.64*	*-0.56*	*-0.92*	-28.35	-27.30	3.45	2.06	0.60	0.64
AU351	Barnett		*3.10*	*-0.60*	*-0.43*	-28.38	-27.24	3.49	2.34	**0.75**	0.68
AU034	Turtle	2721	*1.78*	*-1.22*	*-0.74*	-28.02	-27.03	2.41	3.04	0.71	0.02
AU352	Barnett		*3.43*	*-1.66*	*-0.22*	-28.34	-27.29	3.02	3.68	0.90	0.11
AU029	Barnett	2408	*4.38*	*-0.32*	*-1.22*	-28.28	-27.28	3.30	9.24	1.11	0.06
Family 'Sahul'											
AU049	Sunrise	2206	*-2.16*	*-2.58*	*0.68*	-27.81	-25.80	1.52	1.11	0.24	0.04
AU052	Swan	2330	*-0.80*	*-1.29*	*-0.06*	-27.32	-27.88	1.64	1.36	0.34	0.04
AU050	Sunrise	2206	*-3.69*	*-3.54*	*0.22*	-27.70	-26.09	0.80	1.37	0.27	0.03
AU051	Swan	2364	*-0.61*	*-2.91*	*0.71*	-27.40	-26.21	1.86	1.81	0.42	0.03
Timor Seeps											
ID122	Paulaca		*1.27*	*-0.64*	*-1.84*	-30.01	-28.65	2.61	1.04	0.34	0.01
ID123	Aliambata		*0.60*	*-0.50*	*-1.77*	-29.92	-28.78	2.09	0.82	0.35	0.01
Bintuni: Miocene Shale Source											
ID120	Jagiro	255	*-0.63*	*-2.13*	*3.42*	-22.94	-21.12	1.92	0.75	0.39	0.02
ID119	Mogoi		*-0.06*	*-2.40*	*3.75*	-22.57	-20.42	1.87	0.88	0.40	0.01
ID118	Wasian	1055	*0.13*	*-2.47*	*3.72*	-22.28	-20.43	1.86	1.05	0.36	0.03
Seram: Jurassic? Carbonate Source											
ID139	Nief East	1756	*-4.69*	*-1.32*	*-4.17*	-29.02	-29.27	0.10	0.15	0.08	0.01
ID176	Bula		*-3.93*	*-2.17*	*-3.09*	-29.12	-28.76	0.21	0.28	0.12	0.01
Vagrants											
ID157	Wiriagar					-25.71	-23.84	2.90	0.59	0.21	0.01
AU053	Troubadour	2244	*-3.21*	*1.00*	*-0.17*	-27.92	-25.68	3.57	0.72	0.15	0.01
AU353	Petrel		*1.75*	*2.48*	*2.54*	-24.57	-23.12	4.69	2.04	0.99	0.06

Family L/G (Petrel Barnett and Turtle fields) contains high values for this marker. This parameter was not used in the multivariate analyses since it is not source related.

Examining the carbon isotope data of Family W2V, it becomes apparent that the three Puffin oils have anomalous heavy values compared to the other W2V oils. The differences are too large to be caused by thermal maturity. Therefore, it is postulated that the Puffin oil Cretaceous reservoirs have been charged with oil from at least two different sources. The primary source is that which generated the rest of the W2V oils (e.g., Challis and Jabiru oils) containing the biomarkers which grouped the Puffin oils within Family W2V. In addition, a mature oil, containing very low concentrations of biomarkers, but isotopically heavy in the bulk hydrocarbon fractions, mixed with the W2V oil source, probably in the Cretaceous reservoirs in the Puffin field. A more mature Petrel oil (AU353), with its heavy isotope composition, may be the other source.

Figure III-17 illustrates thermal maturity trends within the different oil families by plotting the C27 and C29 terpane maturity parameters Ts/Tm. These parameters can also be source dependent, and it is not usually valid to compare maturities between different families. As can be seen in **Table III-2** and **Figure III-17**, Jabiru oils are much more mature than the other members of Family W2V. Talbot and Skua oils are the least mature with Challis intermediate. Family L/G oils shown another maturity trend consistent with a different source. (Some of the C29 Ts/Tm values have been corrected because of an interfering compound as seen in **Figure III-7a**; these corrected values are in bold type in **Table III-2**).

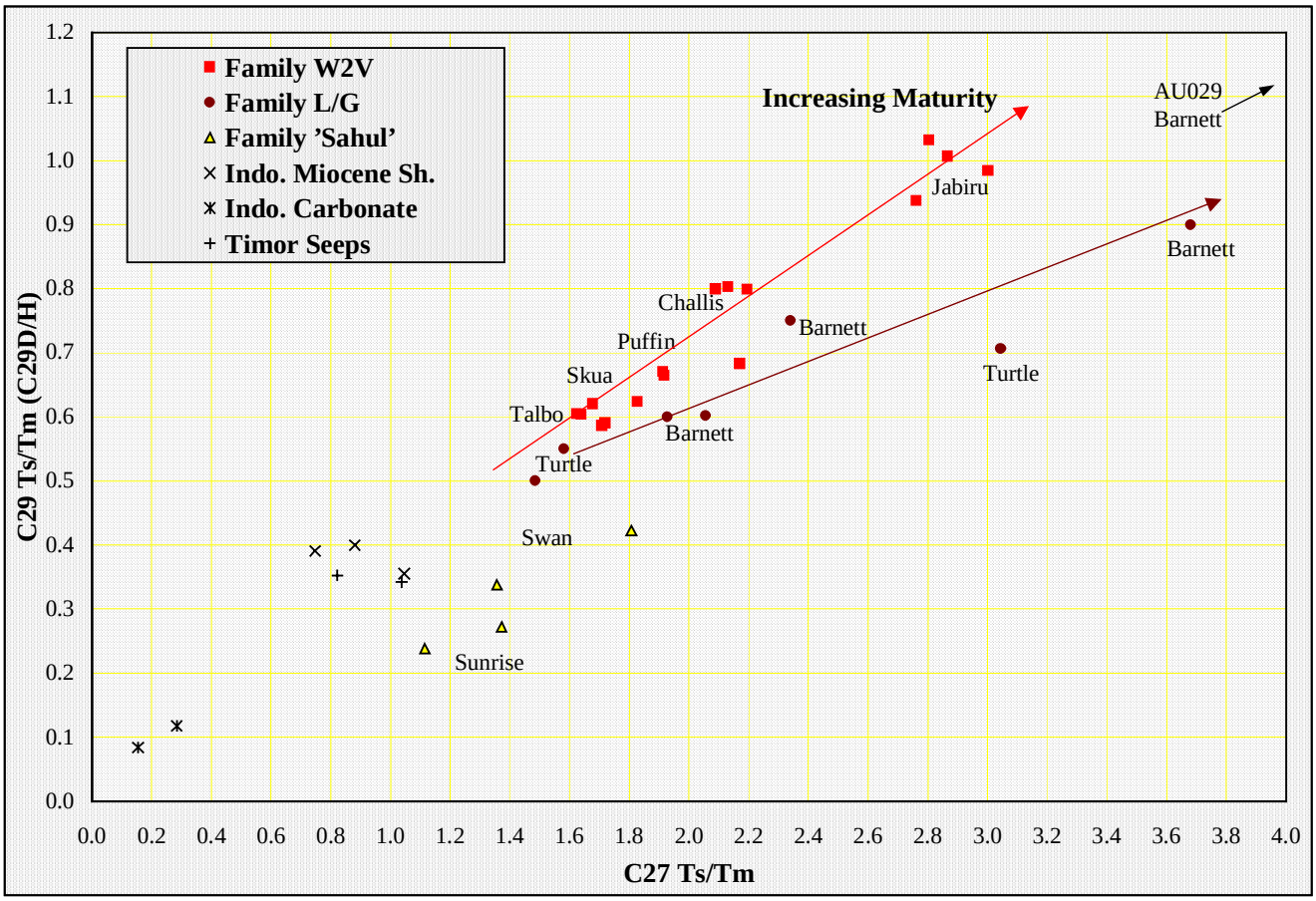


Figure III-17. Terpane Thermal Maturity: Bonaparte Basin.

CANNING BASIN

The Canning Basin dendrogram and PCA diagram are shown in **Figures III-18** and **III-19**, respectively. Three major oil families are apparent. Oils from the West Terrace, Lloyd, Sundown, and Meda fields are strongly related with higher diahopanes and diasteranes, as well as higher Pr/Ph and n-C27/C17 ratios. This family is labeled Family L/G Transitional. These oils appear to have a source similar to Petrel sub-basin oils but have not suffered paleobiodegradation. The Devonian reservoired Blina and Janpam North fields are characterized by high gammacerane content, steranes/hopanes, and % C27 regular steranes. The high gammacerane and low Pr/Ph values reflect deposition of source sediments in a rather restricted or stratified water column, perhaps caused by salinity gradients. Ordovician reservoired oils Dodonea and Pictor comprise the third Family L2. These are the oils which have the highly characteristic *G. prisca* paraffin signature. Devonian Mirbelia oil appears to be a vagrant, not easily typed with the other Canning Basin oils, and may represent yet another source rock facies.

Family Summary Table and Thermal Maturity

Summary **Table III-3** lists the oil samples and field names within each family as determined by the various cluster and principal component analyses. In addition, the oils are listed in order of increasing thermal maturity based on C27 terpane Ts/Tm ratios within each sub family. The principal component values, carbon isotope composition, and other maturity parameters (C29 Ts/Tm or 29D/H and diasteranes/regular steranes S1/S6) are also listed for each oil.

Table III-3. Canning Oil Families; Listed in Order of Increasing Thermal Maturity.

Field/Well		Depth (m)	*PC 1*	*PC 2*	*PC 3*	13Cs	13Ca	S1/S6	Ts/Tm	29D/H
Family L3										
AU143	Janpam N.	1662	*-4.10*	*-0.55*	*0.40*	-29.23	-26.81	0.53	1.13	0.52
AU140	Blina	1489	*-4.05*	*-0.18*	*0.64*	-29.21	-27.24	0.99	1.16	0.41
AU141	Blina	1472	*-3.94*	*-0.30*	*0.56*	-29.18	-27.16	0.99	1.21	0.39
AU329	Blina	1813	*-4.07*	*-0.42*	*-0.02*	-29.26	-27.26	0.87	1.23	0.38
Family L/G										
AU145	Meda	1564	*1.02*	*1.50*	*-0.99*	-27.31	-27.20	2.95	2.28	0.65
AU150	W. Terrace	1159	*1.37*	*2.07*	*0.19*	-27.91	-27.77	3.60	3.17	0.85
AU149	Sundown	1480	*1.86*	*1.13*	*-1.13*	-28.82	-28.33	3.95	3.18	0.87
AU148	Sundown	1098	*1.66*	*1.04*	*-1.29*	-28.81	-28.32	3.66	3.19	0.86
AU151	W. Terrace	1198	*1.50*	*2.14*	*0.23*	-27.86	-27.77	3.82	3.26	0.81
AU144	Lloyd	1523	*1.30*	*2.66*	*0.36*	-27.05	-27.17	3.65	3.65	0.95
Family L2										
AU142	Dodonea	1554	*1.51*	*-3.74*	*-2.93*	-31.48	-31.75	1.70	0.62	0.23
AU147	Pictor	956	*2.24*	*-3.23*	*-0.21*	-31.10	-29.93	2.42	0.63	0.17
Vagrant										
AU146	Mirbelia	1847	*3.70*	*-2.13*	*4.17*	-30.21	-29.40	2.34	1.20	0.48

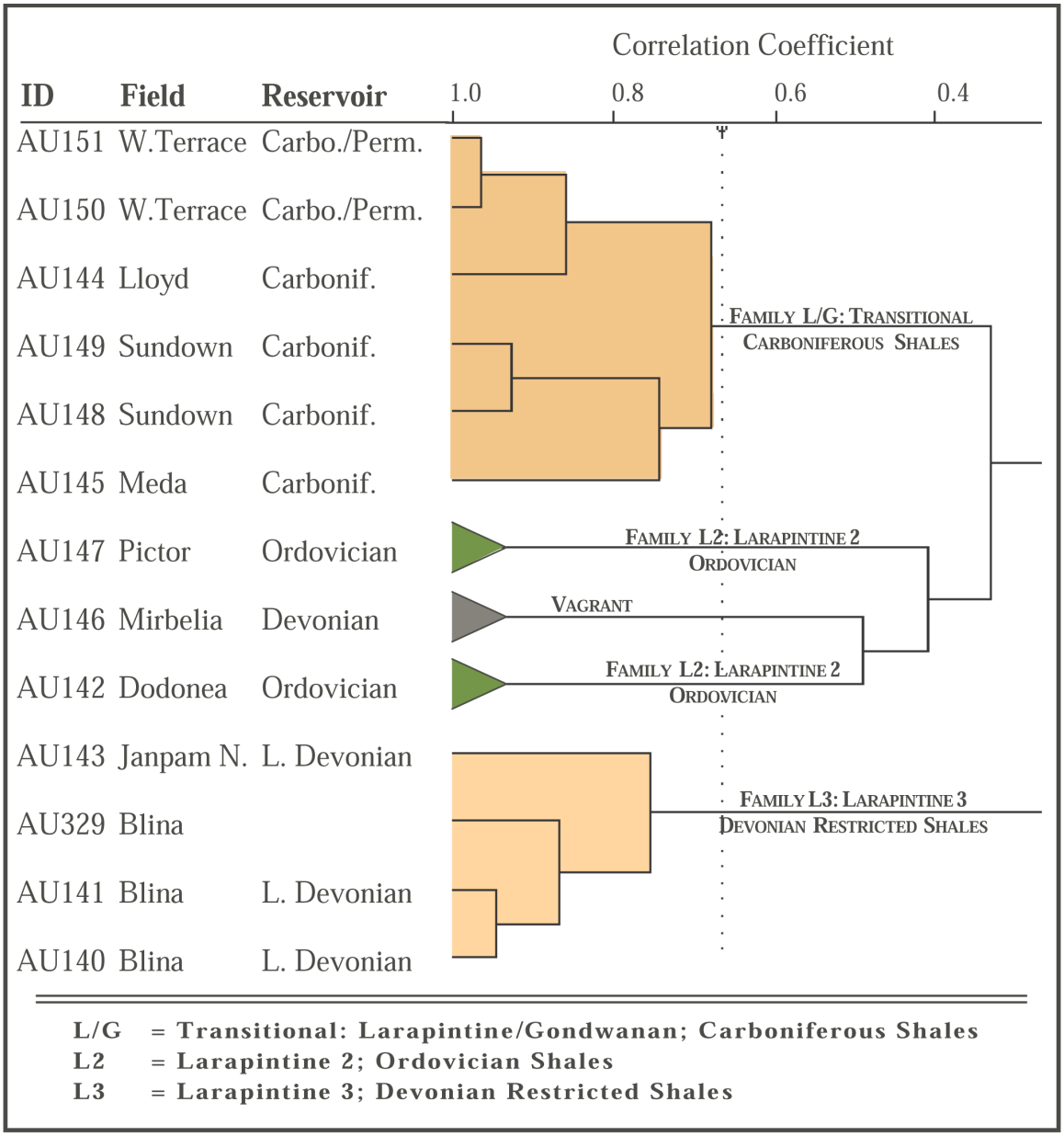


Figure III-18. Cluster Analysis Dendrogram: Canning Basin.

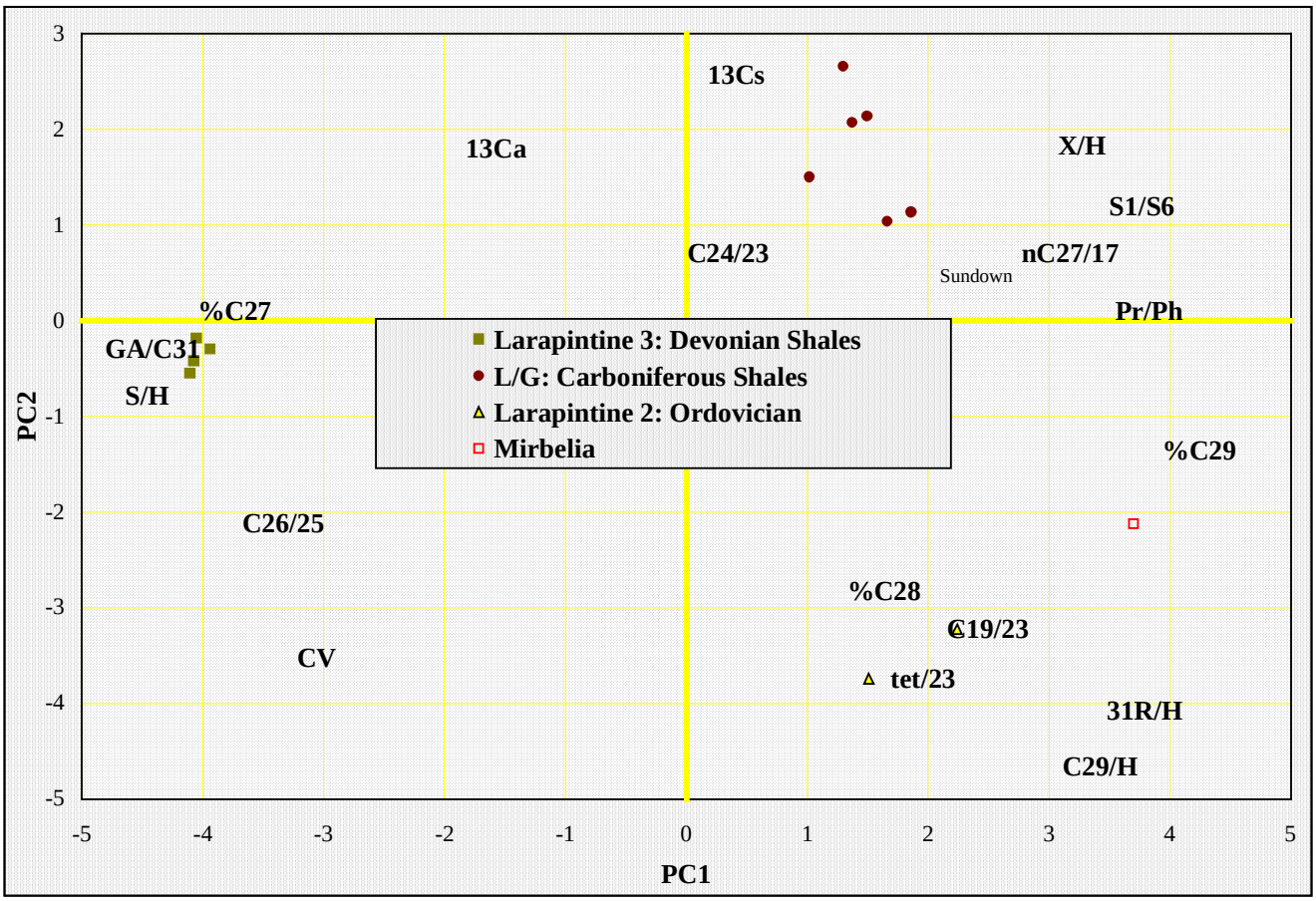


Figure III-19. Principle component scores and loadings: Canning Basin.

The two Carboniferous-reservoired Sundown oils of Family L/G have bulk hydrocarbon carbon isotope compositions of about 1 ‰ lighter than the other oil family members (**Table III-3**). It is likely that these oils contain another source component, derived from the Ordovician. PC2 values for Sundown oils are pulled toward the Ordovician L2 Family oils of Pictor and Dodonea (**Figure III-19**) suggesting mixing consistent with the biomarker distribution also.

The terpane thermal maturity plot for Canning oils is given in **Figure III-20**. Lloyd oil appears more mature than Meda with Sundown and West Terrace intermediate within the L/G Family. Although L3 and L2 Family members have lower Ts/Tm values than L/G oils, the different source horizons preclude inter family maturity comparisons using these terpane parameters.

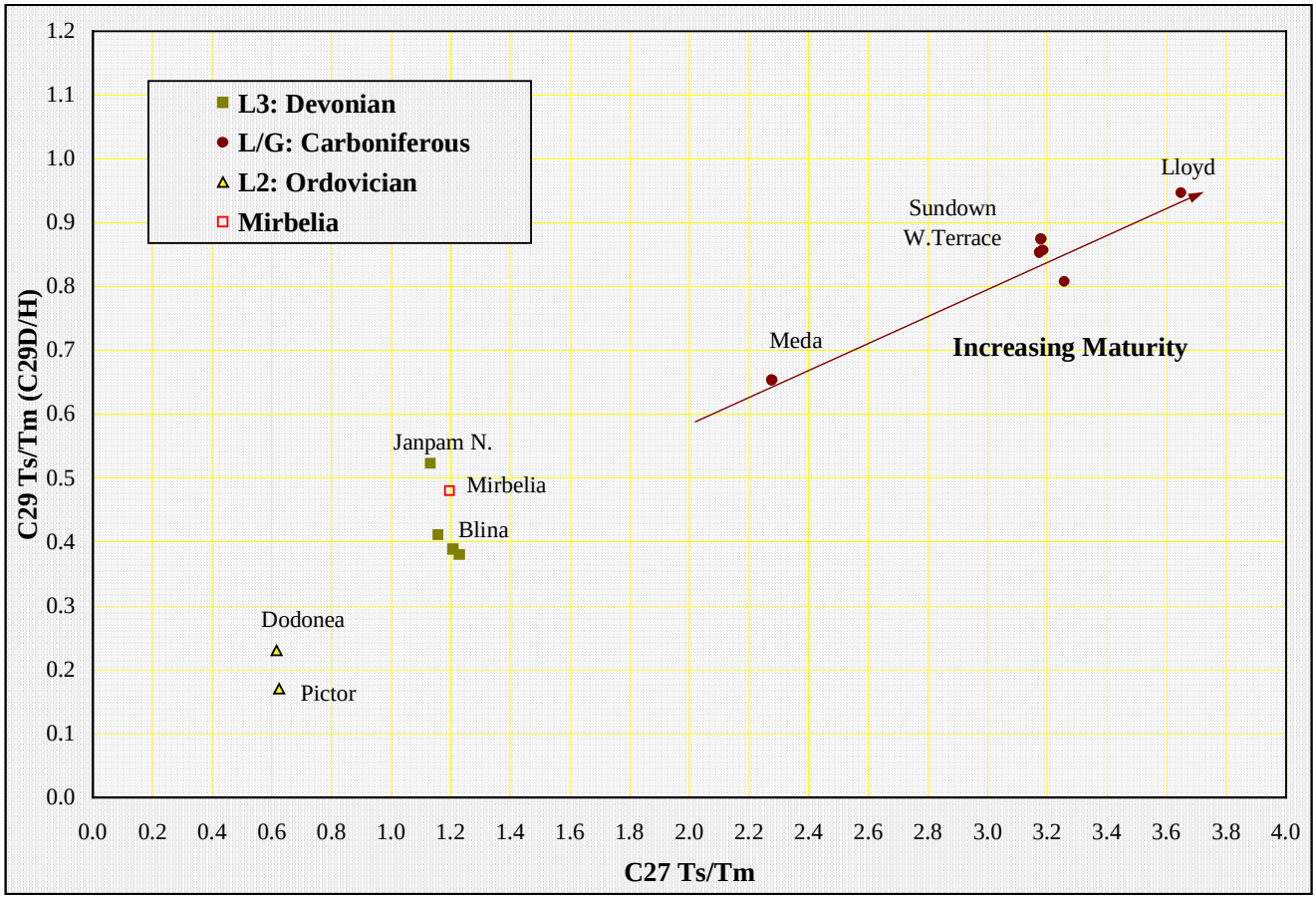


Figure III-20. Terpane Thermal maturity: Canning Basin.

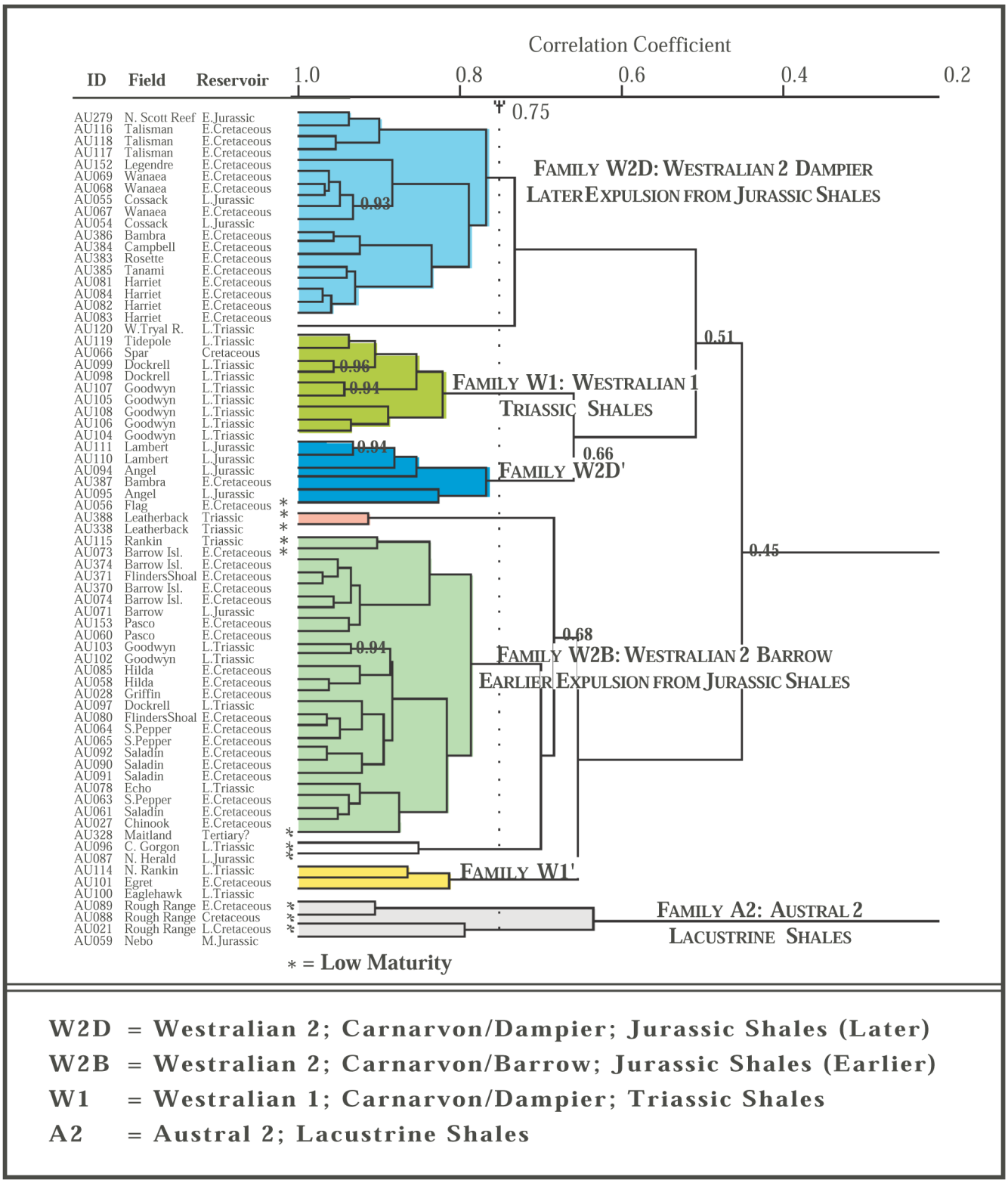
CARNARVON BASIN

The Carnarvon Basin dendrogram and PCA diagrams are shown in **Figures III-21** and **III-22,23**, respectively. About 15 samples were excluded from the cluster and principal component analyses because of their lack of biomarkers. These condensates, for the most part, are simply too mature to contain appreciable concentrations of the high molecular weight terpanes and steranes that can be measured by conventional GC/MS techniques. The North Scott Reef sample (AU279) from the Browse Basin and the Nebo oil (AU059) from the Beagle sub-basin to the north are included as are the Rough Range and Leatherback samples from the Exmouth sub-basin. The majority of the samples are from the Dampier and Barrow sub-basins of the Carnarvon.

Correlation coefficients are shown on the **Figure III-21** dendrogram for many of the samples from the same reservoir; these are typically high, ranging between 0.93 and 0.96. These same samples are connected in the PC1 versus PC2 plot of **Figure III-22**, indicating the small variation expected among samples from the same reservoir.

Seven oil families can be recognised on the dendrogram and PCA plots. The two major families are labeled W2D and W2B, and contain predominantly oils from fields located in the Dampier and Barrow sub-basins, respectively. There are some notable exceptions, however. Oils from the Barrow sub-basin Harriet, Rosette, Campbell, and Bambra field complex correlate well with Wanaea, Cossack, and Talisman oils of the eastern part of the Dampier sub-basin far to the north rather than the closer Barrow field oils to the south. Interestingly, the Browse Basin North Scott Reef oil is also a member of Family W2D, indicating a very similar source rock within the two basins. The geochemical parameters responsible for the differences in Families W2D and W2B are primarily loaded in PC2 (**Figures III-22** and **III-23**). These include high values for %C27 steranes, Steranes/Hopanes, C31/C30 hopanes and more positive carbon isotope values for Family W2D. Family W2B oils have higher %C29 steranes and tricyclic terpane C24/C23 ratios.

Principal component 1 separates Family A2 from the other Carnarvon oils. These terrigenous-sourced oils are recognised as such by the high waxy component (n-C27/C17) and other markers for nonmarine organic mater (high tricyclic terpane C19/C23, %C29 steranes, and Pr/Ph values). Rough Range and Nebo oils belong to this Family A2 of land plant/lacustrine derived oils. The correlation is somewhat loose within Family A2, suggesting a similar source depositional environment rather than the exact same source rock for the widely spaced Beagle and Exmouth sub-basins. Leatherback oils also appear to have a major terrigenous component (e.g., high %C29 steranes, low Steranes/Hopanes). These oils are at a low level of thermal maturity (**Figure III-9b**), however, which can effect their statistical grouping. Still, Leatherback oils were probably generated from a different, albeit nonmarine facies than the slightly more mature Rough Range oils.



W2D = Westralian 2; Carnarvon/Dampier; Jurassic Shales (Later)
W2B = Westralian 2; Carnarvon/Barrow; Jurassic Shales (Earlier)
W1 = Westralian 1; Carnarvon/Dampier; Triassic Shales
A2 = Austral 2; Lacustrine Shales

Figure III-21. Cluster analysis Dendrogram: Carnarvon Basin.

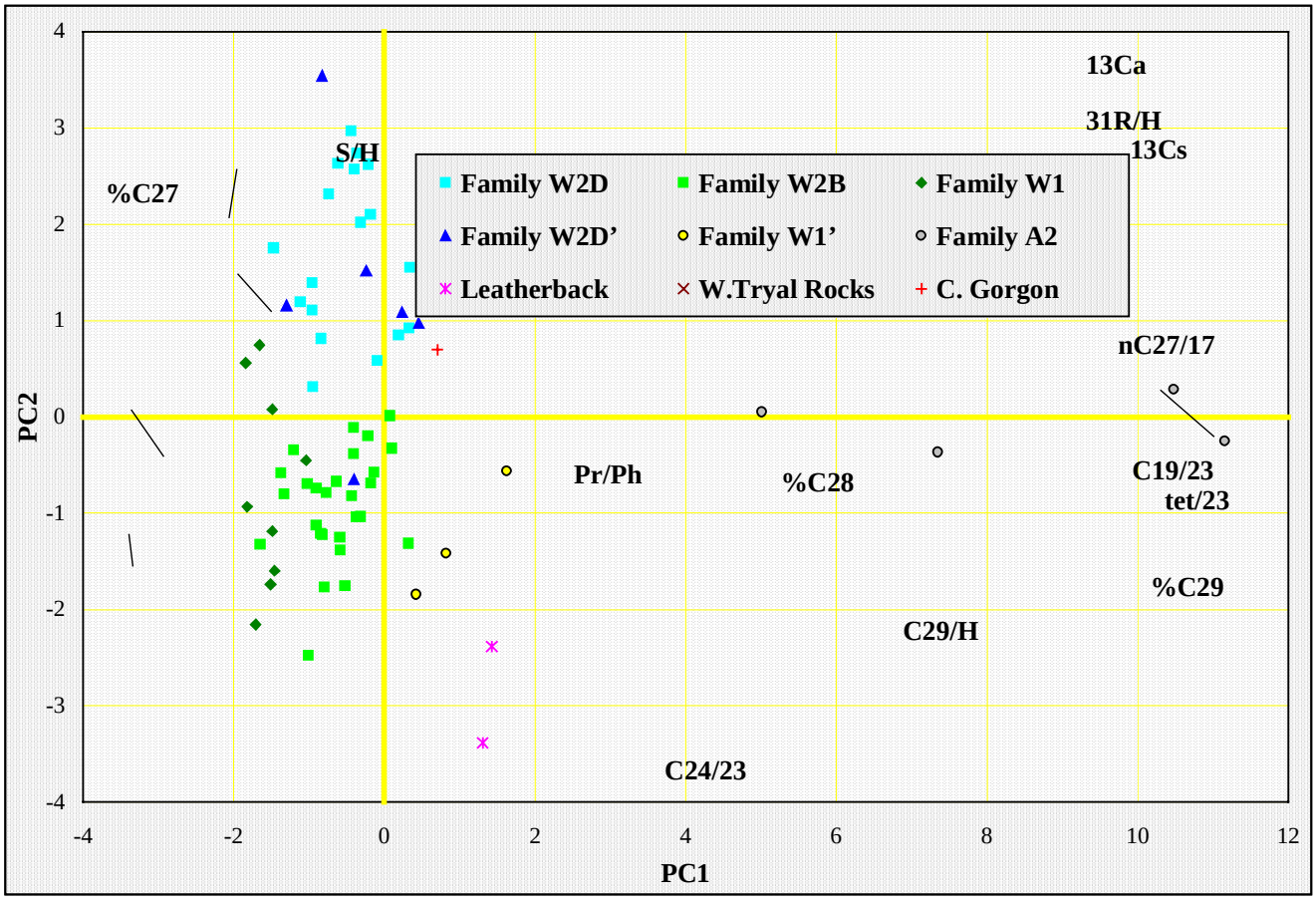


Figure III-22. Principle component scores and loadings plot: Carnarvon Basin.

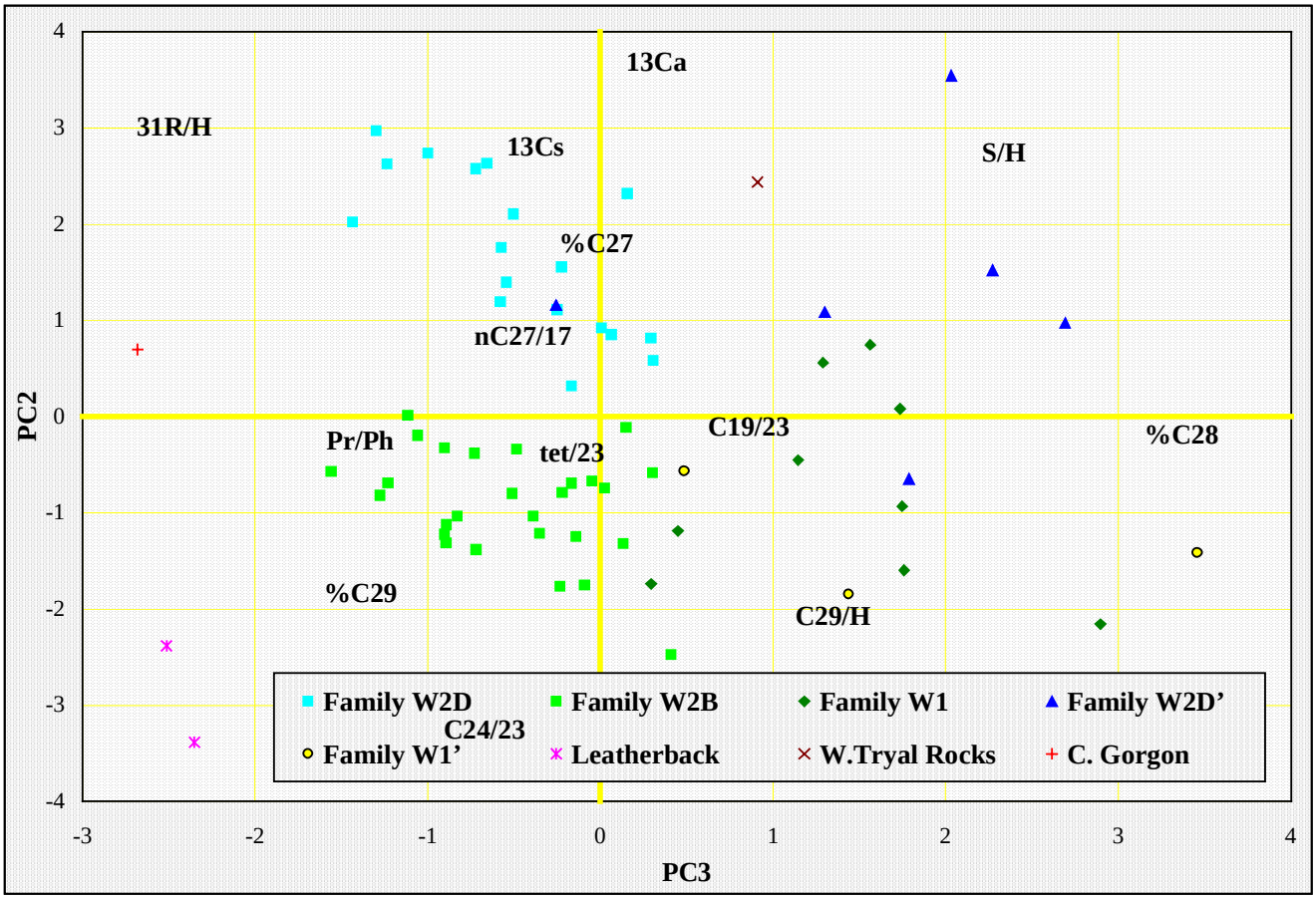


Figure III-23. Principle components PC2 versus PC3.

Family W1 oils (Goodwyn, Dockrell, and Tidepole) from the western Dampier sub-basin separate from the W2 oil families based on PC3 (**Figure III-23**) with higher %C28 steranes and C29/C30 hopane ratios. Goodwyn-1 oils (AU102 and AU103) fall within Family W2B rather than Family W1 where the oils from subsequent Goodwyn wells (wells 3-7) are members. Family W2D' oils from Angel and Lambert fields differ from Family W2D also in PC3 and may represent a slight variation in the organofacies of the W2D source rock. Spurious oils within these two families maybe due to variations in thermal maturity. These samples include very mature Spar (AU066) in Family W1, very mature Bambra (AU387) and low mature Flag (AU056) in Family W2D'.

Family W1' consists of only three oils from the nearby North Rankin, Egret, and Eaglehawk fields. They may represent a slightly more terrigenous facies of the Goodwyn and Dockrell source rocks (Family W1) as indicated in PCA **Figures III-22** and **III-23**. Outlier or vagrant oils include West Tryal Rocks (AU120), Central Gorgon (AU096), and North Herald (AU087). Unique source facies and/or maturity variations are likely responsible for the lack of clear correlations.

Family Summary Table and Thermal Maturity

Summary **Table III-4** lists the oil samples and field names within each family as determined by the various cluster and principal component analyses. In addition, the oils are listed in order of increasing thermal maturity based on C27 terpane Ts/Tm ratios within each sub family. The principal component values, carbon isotope composition, and other maturity parameters (C29 Ts/Tm or 29D/H and diasteranes/regular steranes S1/S6) are also listed for each oil. The biodegradation marker (DM/H) is also listed.

Table III-4. Carnarvon Oil Families; Listed in Order of Increasing Thermal Maturity.

	Field/Well	Depth (m)	*PC 1*	*PC 2*	*PC 3*	13Cs	13Ca	S1/S6	Ts/Tm	29D/H	DM/H
Family W2D											
AU279	N. Scott Reef	4283	*0.3*	*0.9*	*0.0*	-26.96	-24.48	3.00	1.39	0.46	0.02
AU116	Talisman	1968	*0.3*	*1.6*	*-0.2*	-26.57	-24.50	3.81	1.80	0.60	0.02
AU118	Talisman	1927	*-0.1*	*0.6*	*0.3*	-26.45	-24.67	3.66	1.86	0.62	0.01
AU117	Talisman	1957	*0.2*	*0.8*	*0.1*	-26.64	-24.50	3.69	1.98	0.60	0.01
AU152	Legendre	1898	*-0.2*	*2.1*	*-0.5*	-26.47	-24.47	3.68	2.22	0.61	0.01
AU054	Cossack	2956	*-0.3*	*2.0*	*-1.4*	-26.18	-24.37	3.82	2.98	0.93	0.01
AU055	Cossack	2956	*-0.2*	*2.6*	*-1.2*	-26.22	-24.36	3.69	2.98	0.97	0.01
AU067	Wanaea	2897	*-0.4*	*2.6*	*-0.7*	-25.97	-24.35	3.44	3.25	1.01	0.02
AU069	Wanaea	2918	*-0.4*	*3.0*	*-1.3*	-26.13	-24.65	3.87	3.32	1.06	0.02
AU083	Harriet	1946	*-1.0*	*1.4*	*-0.5*	-26.85	-25.28	2.78	3.33	0.92	0.09
AU081	Harriet	1922	*-0.8*	*0.8*	*0.3*	-26.81	-25.27	2.76	3.35	0.91	0.09
AU068	Wanaea	2910	*-0.4*	*2.7*	*-1.0*	-26.14	-24.60	3.59	3.38	1.04	0.02
AU084	Harriet	1916	*-1.0*	*1.1*	*-0.2*	-26.79	-25.28	2.91	3.39	0.93	0.09
AU082	Harriet	1910	*-1.1*	*1.2*	*-0.6*	-26.73	-25.19	2.68	3.40	0.86	0.08
AU386	Bambra	2034	*-0.6*	*2.6*	*-0.7*	-26.25	-24.83	3.50	3.46	0.91	0.04
AU385	Tanami	2180	*-0.9*	*0.3*	*-0.2*	-26.62	-25.70	3.11	3.56	0.84	0.08
AU383	Rosette	2396	*-1.5*	*1.8*	*-0.6*	-26.43	-25.30	3.83	3.74	0.83	0.05
AU384	Campbell	2216	*-0.7*	*2.3*	*0.2*	-26.53	-25.12	3.82	3.75	0.92	0.13
AU057*	Harriet	1922				-25.77	-26.97				

Table III-4. Carnarvon Oil Families (cont.).

	Field/Well	Depth (m)	*PC 1*	*PC 2*	*PC 3*	13Cs	13Ca	S1/S6	Ts/Tm	29D/H	DM/H
Family W2B											
AU087	North Herald	1735	*-0.9*	*-1.1*	*-0.9*	-27.05	-26.26	0.83	0.61	0.23	0.11
AU085	Hilda	2669	*-0.4*	*-0.4*	*-0.7*	-27.12	-25.38	2.65	1.36	0.43	0.08
AU060	Pasco	1832	*0.3*	*-1.3*	*-0.9*	-26.56	-25.82	0.50	1.38	0.42	0.08
AU058	Hilda	2670	*-0.8*	*-1.2*	*-0.4*	-26.87	-26.28	2.77	1.38	0.44	0.09
AU328	Maintland	1289	*-1.4*	*-0.6*	*0.3*	-26.57	-26.07	1.00	1.43	0.47	0.01
AU027	Chinook	2654	*-0.8*	*-0.8*	*-0.2*	-26.93	-26.42	3.11	1.45	0.38	0.06
AU028	Griffin	2664	*-0.8*	*-1.2*	*-0.9*	-27.04	-26.23	3.54	1.50	0.43	0.08
AU153	Pasco	1754	*-0.2*	*-0.2*	*-1.1*	-26.50	-25.90	1.08	1.62	0.51	0.00
AU091	Saladin	1117	*-1.6*	*-1.3*	*0.1*	-27.25	-26.37	2.30	1.77	0.64	0.19
AU102	Goodwyn-1	2847	*-1.0*	*-2.5*	*0.4*	-27.26	-26.49	1.98	1.78	0.54	0.44
AU371	Flinders Shoal	799	*-0.1*	*-0.6*	*-1.6*	-26.77	-25.89	1.08	1.80	0.57	0.20
AU078	Echo	2993	*-0.9*	*-0.7*	*0.0*	-27.12	-26.09	1.65	1.84	0.60	0.62
AU097	Dockrell	3009	*-0.3*	*-1.0*	*-0.8*	-27.27	-25.89	1.54	1.85	0.65	0.48
AU065	S. Pepper		*-0.6*	*-1.4*	*-0.7*	-26.69	-26.06	1.63	1.87	0.63	0.28
AU090	Saladin	1129	*-1.3*	*-0.8*	*-0.5*	-27.24	-26.39	2.16	1.88	0.61	0.14
AU063	S. Pepper	2217	*-0.6*	*-0.7*	*0.0*	-26.81	-26.12	1.52	1.89	0.62	0.26
AU092	Saladin	1116	*-1.0*	*-0.7*	*-0.2*	-27.29	-26.36	2.58	1.90	0.60	0.16
AU115	Rankin	2954	*-0.5*	*-1.8*	*-0.1*	-27.11	-26.02	1.52	1.91	0.66	0.50
AU080	Flinders Shoal	2622	*-0.4*	*-1.0*	*-0.4*	-26.93	-26.00	1.15	1.93	0.61	0.21
AU064	S. Pepper		*-0.6*	*-1.3*	*-0.1*	-26.84	-26.03	1.49	1.97	0.62	0.27
AU103	Goodwyn-1	2847	*-0.8*	*-1.8*	*-0.2*	-27.42	-26.37	1.81	1.98	0.67	0.43
AU061	Saladin		*-1.2*	*-0.3*	*-0.5*	-27.17	-26.46	2.26	2.02	0.65	0.17
AU073	Barrow Island		*-0.4*	*-0.1*	*0.2*	-26.70	-25.97	1.16	2.06	0.57	0.17
AU370	Barrow Island		*-0.2*	*-0.7*	*-1.2*	-26.81	-25.88	1.32	2.08	0.66	0.19
AU374	Barrow Island	859	*-0.4*	*-0.8*	*-1.3*	-26.58	-25.99	1.83	2.46	0.65	0.11
AU071	Barrow	2068	*0.1*	*-0.3*	*-0.9*	-26.60	-25.56	1.65	3.11	0.73	0.02
AU074	Barrow Island	2312	*0.1*	*0.0*	*-1.1*	-26.72	-25.41	1.48	3.19	0.68	0.02
AU062*	Sinbad	2064				-26.65	-25.39				
AU075*	Chervil	1618				-26.75	-25.46				
AU362*	Barrow Island					-26.68	-26.08				
AU363*	Barrow Island	1692				-26.62	-25.52				
AU072*	Barrow Deep	3429				-25.25	-23.40				
AU382*	Yammaderry	1101				-27.15	-26.31				
AU360*	Australind	1223				-27.13	-27.12				
AU366*	Crest	1160				-27.22	-26.25				
AU079*	Elder	1787				-26.46	-25.00				
AU076*	East Spar	2537				-26.49	-25.64				
AU077*	East Spar	2537				-26.58	-25.63				
Family W1											
AU104	Goodwyn-3	2891	*-1.5*	*-1.6*	*1.8*	-27.34	-25.83	2.42	1.23	0.43	0.33
AU108	Goodwyn-7	2835	*-1.7*	*-2.2*	*2.9*	-27.26	-26.08	8.63	1.34	0.46	0.39
AU105	Goodwyn-4	2903	*-1.5*	*-1.2*	*0.4*	-27.14	-26.16	2.34	1.85	0.62	0.49
AU107	Goodwyn-5	2903	*-1.5*	*-1.7*	*0.3*	-26.97	-26.09	2.48	1.92	0.63	0.54
AU119	Tidepole	3018	*-1.8*	*0.6*	*1.3*	-26.81	-25.47	3.09	1.97	0.56	0.18
AU098	Dockrell	2995	*-1.0*	*-0.5*	*1.1*	-26.98	-25.50	1.76	1.97	0.58	0.60
AU099	Dockrell	2995	*-1.5*	*0.1*	*1.7*	-27.06	-25.38	2.16	2.00	0.62	0.68
AU106	Goodwyn-4	2903	*-1.8*	*-0.9*	*1.7*	-27.17	-26.20	2.71	2.10	0.63	0.57
AU066**?**	Spar	2630	*-1.7*	*0.7*	*1.6*	-26.45	-25.73	6.47	2.78	0.61	0.08

Table III-4. Carnarvon Oil Families (cont.).

	Field/Well	Depth (m)	*PC 1*	*PC 2*	*PC 3*	13Cs	13Ca	S1/S6	Ts/Tm	29D/H	DM/H
Family W2D'											
AU056**?**	Flag	1291	*-1.3*	*1.2*	*-0.3*	-26.78	-25.62	0.70	0.96	0.36	0.07
AU094	Angel	2751	*0.5*	*1.0*	*2.7*	-26.93	-24.55	5.90	1.42	0.50	0.01
AU111	Lambert	3106	*0.2*	*1.1*	*1.3*	-27.08	-24.90	7.56	2.16	0.76	0.02
AU110	Lambert	3106	*-0.2*	*1.5*	*2.3*	-26.96	-24.87	6.72	2.22	0.74	0.04
AU095	Angel	2748	*-0.8*	*3.5*	*2.0*	-26.90	-24.42	7.73	2.52	0.82	0.02
AU093*	Angel	2688				-26.80	-24.32	7.50	3.07	0.83	0.13
AU387**?**	Bambra	3640	*-0.4*	*-0.7*	*1.8*	-27.39	-25.72	4.79	14.10	1.92	0.11
Family W1'											
AU114	N. Rankin		*0.4*	*-1.8*	*1.4*	-27.38	-25.17	4.04	1.15	0.36	0.01
AU101	Egret	3128	*1.6*	*-0.6*	*0.5*	-26.90	-25.37	3.15	1.31	0.42	0.01
AU100	Eaglehawk	2766	*0.8*	*-1.4*	*3.5*	-26.45	-25.48	3.73	1.60	0.62	0.09
AU113*	N. Rankin	2998				-27.22	-25.19				
Family A2											
AU059	Nebo	2668	*5.0*	*0.1*	*-1.2*	-26.71	-24.84	1.34	0.81	0.33	0.01
AU021	Rough Range	1102	*7.3*	*-0.4*	*-0.9*	-24.66	-24.21	0.94	0.39	0.19	0.00
AU088	Rough Range	1102	*11.2*	*-0.3*	*1.2*	-24.65	-24.03	2.13	0.36	0.18	0.02
AU089	Rough Range		*10.5*	*0.3*	*1.5*	-24.68	-24.03	1.89	0.37	0.16	0.02
Vagrants											
AU338	Leatherback		*1.3*	*-3.4*	*-2.4*	-27.46	-26.04	0.68	1.25	0.52	0.01
AU388	Leatherback	1752	*1.4*	*-2.4*	*-2.5*	-27.28	-26.14	0.58	1.40	0.53	0.01
AU120	W. Tryal Rocks	3305	*1.3*	*2.4*	*0.9*	-23.76	-24.69	4.46	1.49	0.41	0.13
AU121*	W. Tryal Rocks	3448				-23.82	-24.71	7.00	1.62	0.50	0.12
AU096	C. Gorgon	4033	*0.7*	*0.7*	*-2.7*	-25.63	-25.24	0.84	0.57	0.20	0.01
AU109*	Gorgon	4002				-25.73	-25.77	4.67	10.67	1.35	0.13
AU112*	N. Gorgon	3759				-25.68	-25.76				

*very low/no biomarkers (condensates)

The terpane maturity trends for the various Carnarvon oil families are illustrated in **Figure III-24**. Beagle Nebo oil is slightly more mature than Exmouth Rough Range samples within Family A2. Exmouth Leatherback is a very low maturity oil based on sterane ratios. Leatherback appears more mature than Rough Range in Figure III-24 because of source differences. In general, W2D oils appear more mature than W2B assuming that the source differences do not obscure the maturity trends. Within Family W2D, Talisman and Legendre oils are less mature than Cossack, Wanaea, and Harriet oils. Within Family W2B, Hilda, Chinook, and Griffin oils are less mature than Saladin and South Pepper oils. Some of the Barrow Island oils appear the most mature.

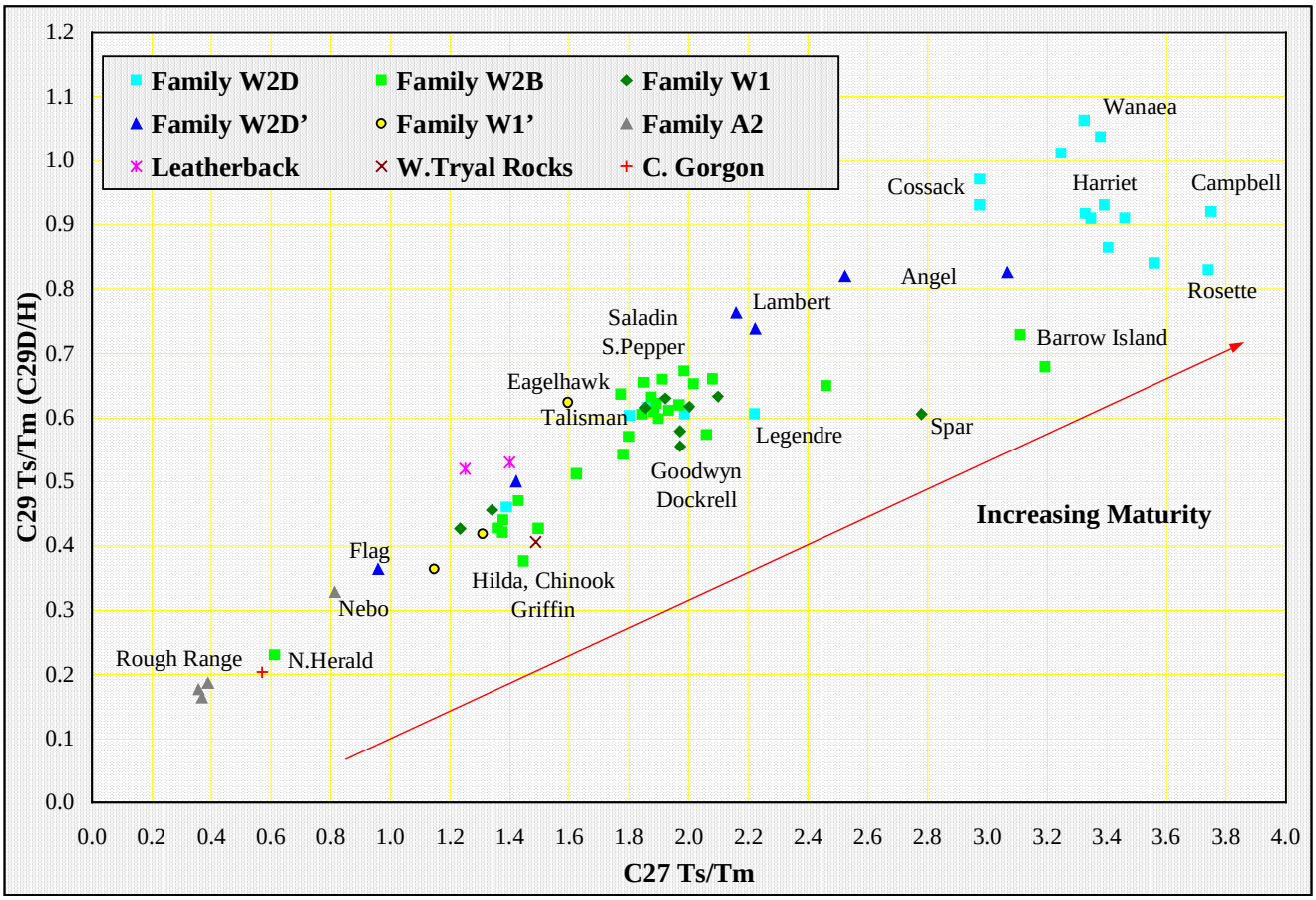


Figure III-24. Terpane thermal maturity: Carnarvon Basin.

PERTH BASIN

The Perth Basin dendrogram and PCA diagram are shown in **Figures III-25** and **III-26**, respectively. Mondarra, Gingin, and one of the Dongara oils were excluded due to very low biomarker concentrations. Family G2 is comprised of oils from Yardarino, Dongara, Erregulla, and Mt. Horner oils, all generated from marine shales. The remaining oils form single well/field families: Walyering, Family A1; Gage Roads, Family A2 (terrigenous/lacustrine); and Whicher Range, Family G1 (possible carbonate source component). Woodada is a vagrant perhaps due to its high maturity, and may be related to Family G2.

Family Summary Table and Thermal Maturity

Summary **Table III-5** lists the oil samples and field names within each family as determined by the cluster and principal component analyses. In addition, the oils are listed in order of increasing thermal maturity based on C27 terpane Ts/Tm ratios within each sub family. The principal component values, carbon isotope composition, and other maturity parameters (C29 Ts/Tm or 29D/H and diasteranes/regular steranes S1/S6) are also listed for each oil.

Table III-5. Perth Oil Families; Listed in Order of Increasing Thermal Maturity.

	Field/Well	Depth (m)	*PC 1*	*PC 2*	*PC 3*	13Cs	13Ca	S1/S6	Ts/Tm	29D/H
Family G2										
AU130	N. Erregulla	2930	*-1.40*	*-0.42*	*0.06*	-32.38	-31.15	0.90	1.46	0.36
AU123	Erregulla	3181	*-1.24*	*-0.56*	*0.31*	-32.31	-31.10	0.79	1.47	0.38
AU129	Mt. Horner	1490	*-1.85*	*-0.04*	*0.00*	-32.68	-31.27	1.08	1.88	0.65
AU122	Dongara	1646	*-1.65*	*0.00*	*0.13*	-32.48	-30.97	1.22	2.50	0.55
AU367	Dongara	1753	*-1.35*	*-0.26*	*0.02*	-32.66	-30.95	1.07	2.55	0.69
AU135	Yardarino	2323	*-2.24*	*-0.20*	*1.16*	-32.57	-29.84	2.46	2.64	0.96
AU137	Yardarino	2323	*-1.81*	*-0.81*	*0.42*	-32.57	-29.76	2.15	3.00	1.08
AU136	Yardarino	2323	*-1.97*	*-0.51*	*0.37*	-32.39	-29.52	2.07	3.67	1.17
AU126*	Mondarra	2700				-31.77	-27.90			
AU127*	Mondarra	2740				-32.48	-29.64			
AU128*	Mondarra	2845				-32.52	-29.24			
AU368*	Dongara	1691				-31.49	-28.08			
Family A1										
AU131	Walyering	3399	*1.03*	*-0.49*	*-1.27*	-27.91	-24.83	1.46	1.08	0.23
AU132	Walyering	3997	*2.04*	*-0.43*	*-3.36*	-27.93	-24.77	3.33	1.83	0.67
Family G1										
AU133	Whicher Range	4205	*3.74*	*3.49*	*0.59*	-26.10	-24.75	1.17	1.33	0.30
Family A2										
AU124	Gage Roads	1782	*7.06*	*-2.19*	*1.52*	-24.52	-23.82	1.30	0.37	0.19
Vagrants										
AU125*	Gingin	3879				-25.53	-24.10			
AU134	Woodada	2500	*-0.36*	*2.41*	*0.06*	-30.58	-27.37	2.53	3.58	0.89

*very low/no biomarkers (condensates)

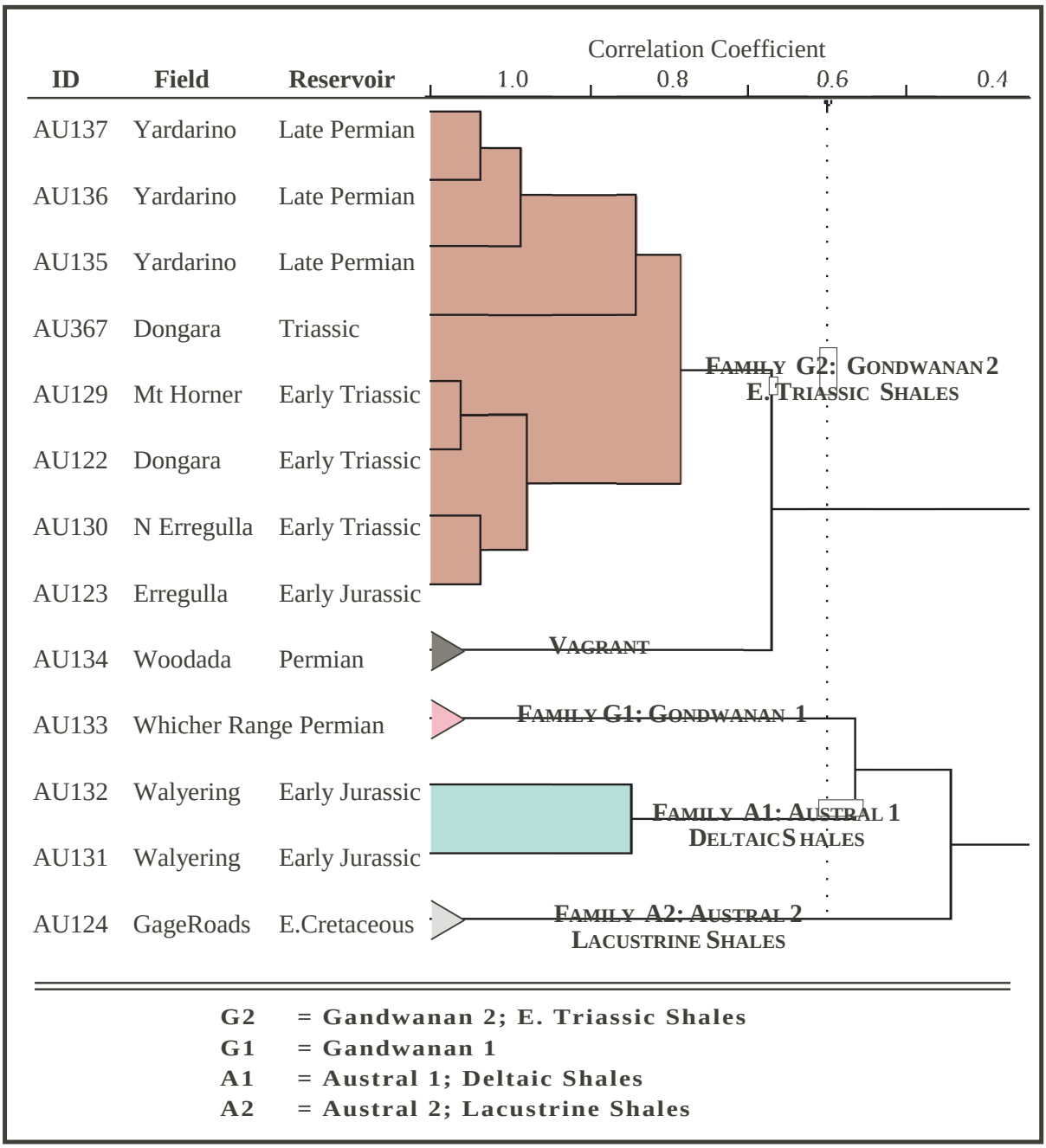


Figure III-25. Cluster Analysis Dendrogram: Perth Basin.

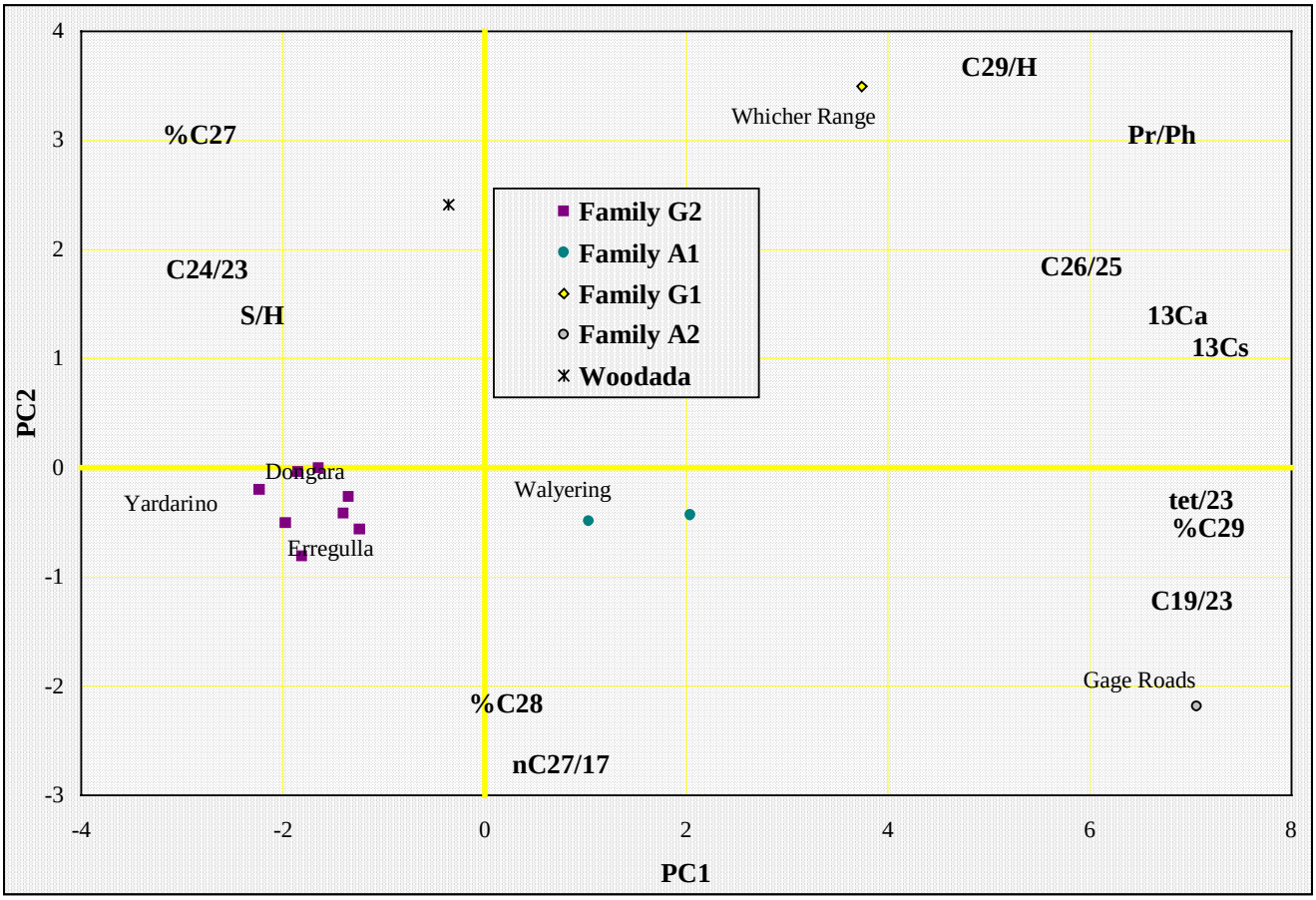


Figure III-26. Principle component scores and loadings plot: Perth Basin.

Figure III-27 is the terpane maturity plot for Perth Basin oils. Within Family G2, Yardarino oils are clearly more mature than Dongara and Mt. Horner oils. Erregulla oils are the least mature members of Family G2. The two Walyering oils have experienced different degrees of thermal stress and is related to reservoir depth. The more mature Walyering-2 sample came from 3997m while the Walyering-1 oil was reservoired at 3399m.

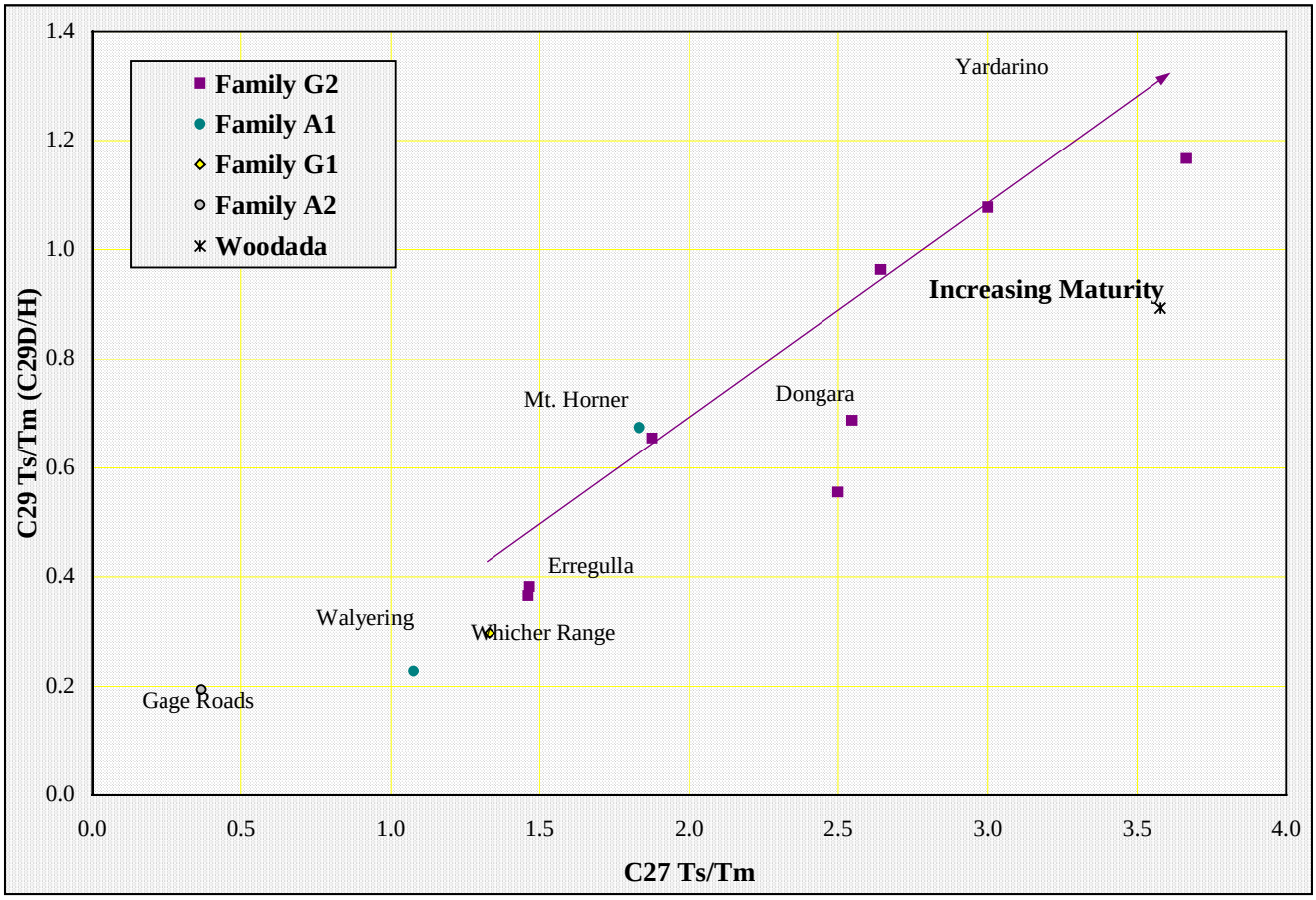


Figure III-27. Terpane thermal maturity: Perth Basin

CHAPTER IV
INTEGRATED DISCUSSION

General Overview of Western Australian Oil Families

The 'big picture' dendrogram shown in **Figure I-2** was constructed using the geochemical data from a representative subset of the west Australian (WA and NT) oils. Samples were chosen to cover the major fields in each basin and the principal families that had been identified in each basin. Further, we only included oils with abundant biomarkers to ensure the comparison could be made using a full spectrum of parameters. The dendrogram can be interpreted as demonstrating the occurrence of a series of petroleum families that differ according to the facies and age of the source rock, migration pathways, the timing of peak hydrocarbon generation and the probable mixing of different liquids in certain reservoirs. It is significant that most of the petroleum families evident in this chemical analysis are strongly aligned with the petroleum systems classification developed by Bradshaw (1993), Bradshaw *et al.* (1994) and the work of the AGSO-APIRA Australian Petroleum Systems Project prior to this study. It is also significant that some groupings of oil families have a tight geographical distribution, while others occur in wells with a wide geographic scatter (**Figure IV-1**). Additional insights can be gleaned from the limited amount of published data on oil-source correlation and the known geographic distribution of particular source rock facies.

Associations that stand out immediately are the tight clustering of oils from single accumulations relative to those in nearby and similarly sourced fields (e.g. Wanaea, Cossack and Talisman in the Dampier; Challis, Talbot and Skua in the Vulcan; Barrow Island, Pasco, South Pepper and Saladin in the Barrow). This observation immediately confirms that the sample pedigrees, sampling protocols and general analytical chemistry that underlies the analysis have been sufficiently rigorous and that the overall approach is sound. Next, when this information is used to evaluate the individual basin dendrograms, the clustering of well established Late Jurassic Westralian oils such as those listed above enables one to identify other oils which have related or very similar source facies (e.g., Talisman and Legendre; Lambert and Angel; Challis and Puffin).

Figure I-2 also shows for the first time that a family of Barrow oils (e.g., Barrow, Pasco, Saladin and South Pepper; denoted W2B) has a source facies that differs from that of the Dampier oils exemplified by Wanaea, Cossack and Talisman and denoted W2D. Of further interest is the closeness of the correlation between the latter group and the Harriet and nearby oils. A feeling for the general similarity of oils from the Late Jurassic Westralian (W2) petroleum system also emerges from the analysis with almost 0.8 correlation coefficient between the W2B and W2V Families and 0.6 between these and W2D. Further, the Vulcan Jabiru oil clusters with the W2D Family when the statistical analysis includes the whole spectrum of west Australian oil types.

Figure I-2 shows Paleozoic oils from the Petrel Sub-basin and Canning Basins clustering together and near to the Triassic oils from the Perth Basin. There is a

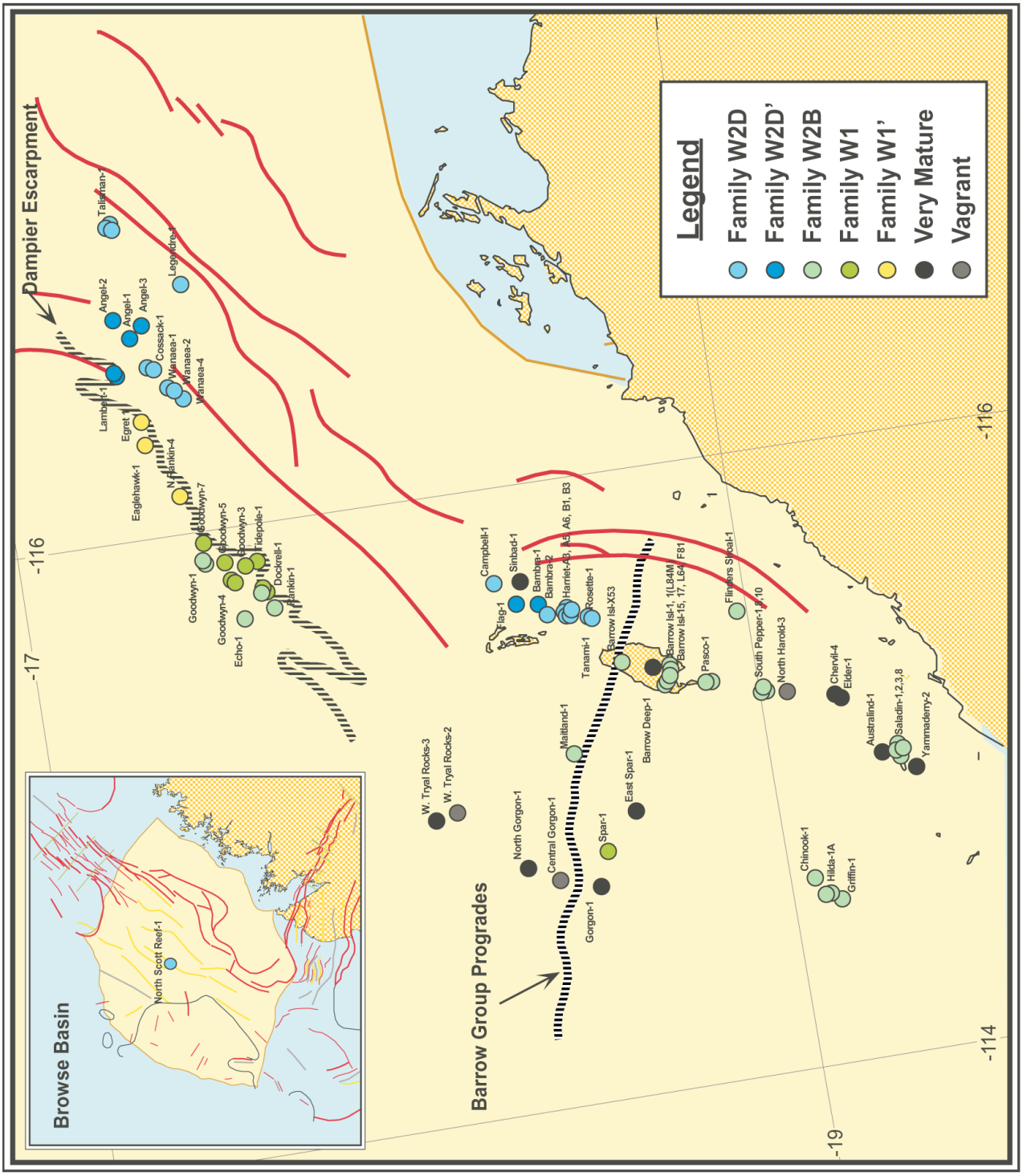


Figure IV-1. Map Showing Geographic Distribution of Carnarvon Basin Oil Families (see **Figure III-21** Dendrogram, p. III-45).

significant correlation between the oils thought to arise from Early Carboniferous source rocks in both the Canning Basin and the Petrel Sub-basin. Finally, there is a family of oils (Nebo, Rough Range and Gage Roads) with wide geographic spread but an obvious source facies association. The biomarker character of these oils indicates a lacustrine source rock in each case and, when one examines the likely candidates, one can make a case for their decreasing age proceeding southwards. This would be consistent with their origin from depocentres created in the earlier stages of rifting prior to breakup (i.e., Argo; ~155 Ma).

Bonaparte Basin Oil Families

Family W2V; Jurassic shales

Five Australian and three Indonesian groupings of oils are evident in the cluster analysis shown in **Figure III-14**. The largest and best represented family (W2V) comprising the Talbot, Skua, Puffin, Challis and Jabiru oils are located within and on the periphery of the Vulcan Sub-basin (**Figure IV-2**) and were probably sourced from Late Jurassic shales (Lower Vulcan Formation) with subtle geochemical differences reflecting variations in both source facies and maturity. For confirmation, see **Figure III-17** (Ts/Tm vs. C29Ts/C29H cross-plot). The trend of increasing maturity seen in the order of Talbot, Skua, Puffin, Challis and Jabiru could also indicate their sequence of generation or their migration pathways when combined with detailed knowledge of local thermal history and/or the structure in this part of the Vulcan Sub-basin. The Swan oils do not appear in the same cluster in this dendrogram (i.e., **Figure III-14**). While this may reflect true differences, we have some reservations about the status of the samples since they were RFT rather than DST and may be affected by drilling fluids. When the statistical analysis is conducted using different combinations of geochemical parameters and oils (data not shown), the Swan oils sometimes cluster with the W2V Family although with a poor correlation coefficient. Hence, they may be 'distant relatives' of the W2V Family.

Family L/G; Carboniferous shales

A second grouping consisting of the L/G Transitional Family, and showing a somewhat poorer correlation coefficient due to wide differences in their respective levels of biodegradation, are all located in the Petrel Sub-basin and probably arise from Early Carboniferous source rocks of the 'lower' Milligans Formation Timor seep oils sit alongside Family L/G although there is no specific genetic relationship.

Family Sahul; Jurassic shales/marls

A third grouping of poorly correlated oils contains Tertiary age Bintuni oils, oils of Seram as well as Swan and Sunrise (termed the Sahul Family). The Sunrise oils and the Troubadour oil, which are located on the northern edge of the Sahul Platform, show biomarker evidence for a calcareous source rock lithology such as lower abundances of diasteranes and diahopane and higher C29H/C30H and indicate that a separate source or source facies is operating in this region.

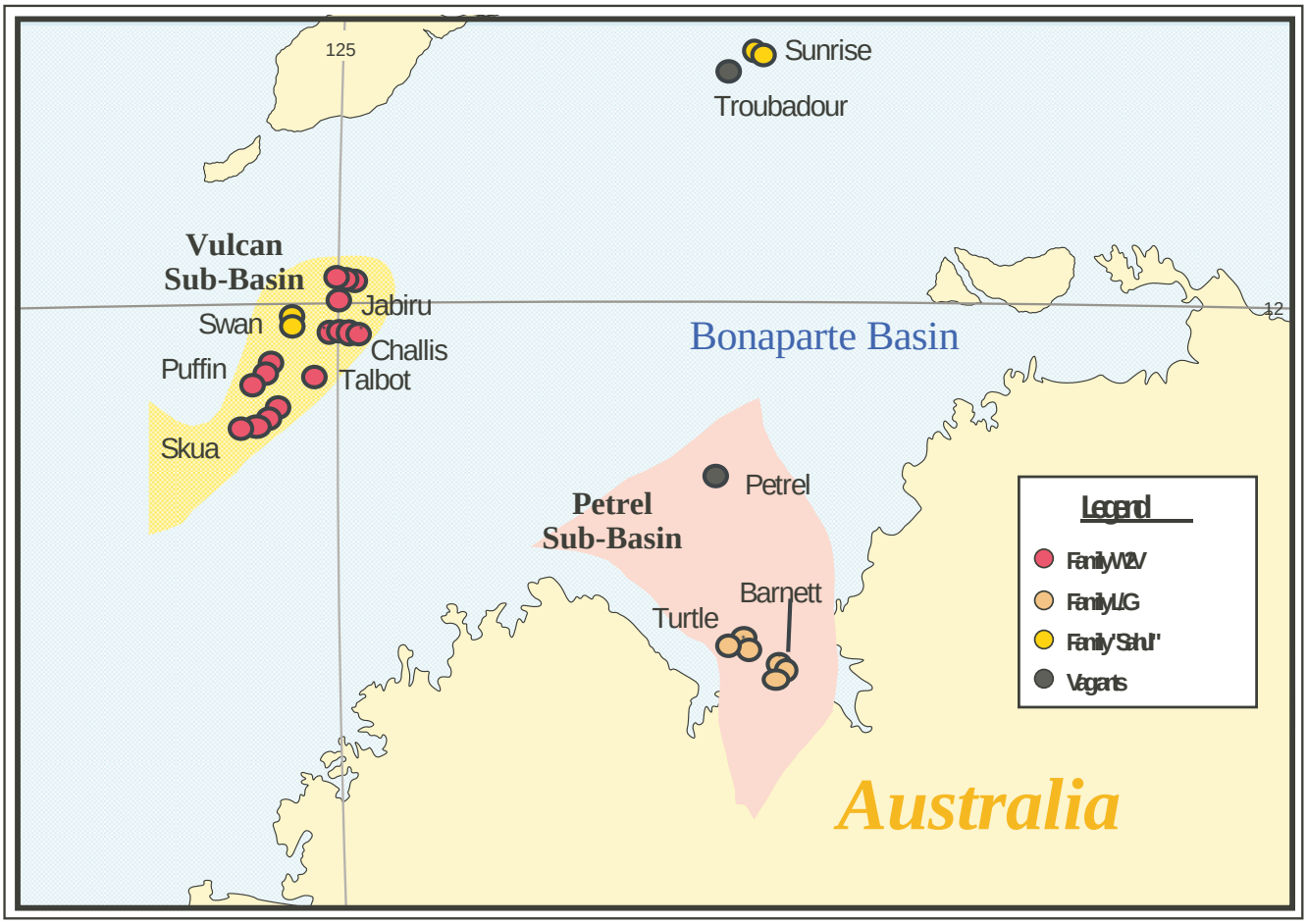


Figure IV-2. Map Showing Geographic Distribution of Bonaparte Basin Oil Families (see **Figure III-14** Dendrogram, p. III-32).

Family G1; Permian sediments

Grouping with Troubadour, although not because of any particular affinity, is the Petrel-4 condensate sourced from probable Permian rocks of the Gondwanan system of the Petrel Sub-basin. The assignment of a Permian source and Gondwanan petroleum system is primarily based on geological considerations. This assignment is supported by the heavy carbon isotopic signature of the sample since it falls in the narrow $\delta^{13}C$ range -23 to -25‰ that characterises Permian oil, coal and carbonaceous shale Australia-wide.

Other points

The large size of the Tern and Petrel (Gondwanan) gas and condensate fields, together with the nearby occurrence of Turtle/Barnett (L/G Transitional) oil family show that the Paleozoic petroleum systems of the region are effective. The isotopic anomaly detected in the Puffin oils also suggests that older rocks may have contributed hydrocarbons to some Mesozoic accumulations. For these reasons, Paleozoic sources should not be discounted in Bonaparte Basin play evaluation.

O'Brien and Woods (1995) recently documented a systematic relationship between the structural integrity of charged Mesozoic traps of the Vulcan Sub-basin and a particular style of carbonate diagenesis in overlying Eocene sandstones. On one hand this shows that trap integrity, rather than source quality or timing considerations, is a major exploration risk in this area. On the other hand, remote sensing methods to detect present day leakage of hydrocarbons, combined with seismic velocity changes through diagenetically-altered sediments to evaluate paleo-leakage, provide an approach to predicting the charge history in this region and, by analogy, in the Carnarvon Basin as well.

Carnarvon Basin Oil Families

Family W2D; Jurassic shales

Results of the cluster analysis of Carnarvon Basin oils is shown in **Figure III-21.** The first grouping termed Dampier Family or W2D, comprises Talisman, Wanaea, Cossack and Legendre oil samples. These are all accumulations located in close proximity at the northern end of the Dampier Sub-basin (**Figure IV-3**). All are reservoired in Late Jurassic / Early Cretaceous sandstones and predominantly contain oil. The generally accepted source of the hydrocarbons is the Late Jurassic restricted marine sediments of the Lewis Trough (e.g. Scott, 1994), the typical source rock of the Westralian Supersystem (Bradshaw *et al*., 1994, Westralian 2).

In some dendrograms based on different combinations of geochemical parameters, some of the Angel samples plot in this field although there are geological reasons for suspecting that the underlying Triassic has contributed, at least in part, to the Angel accumulation, especially as it is gas / condensate rather than oil. In the particular analysis shown in **Figure III-21** Angel and Lambert plot together with a very mature Bambra condensate and a Flag condensate (AU 056) in the dark blue cluster denoted W2D´. The 'undecided' nature of the Angel condensates could be indicating its being predominantly

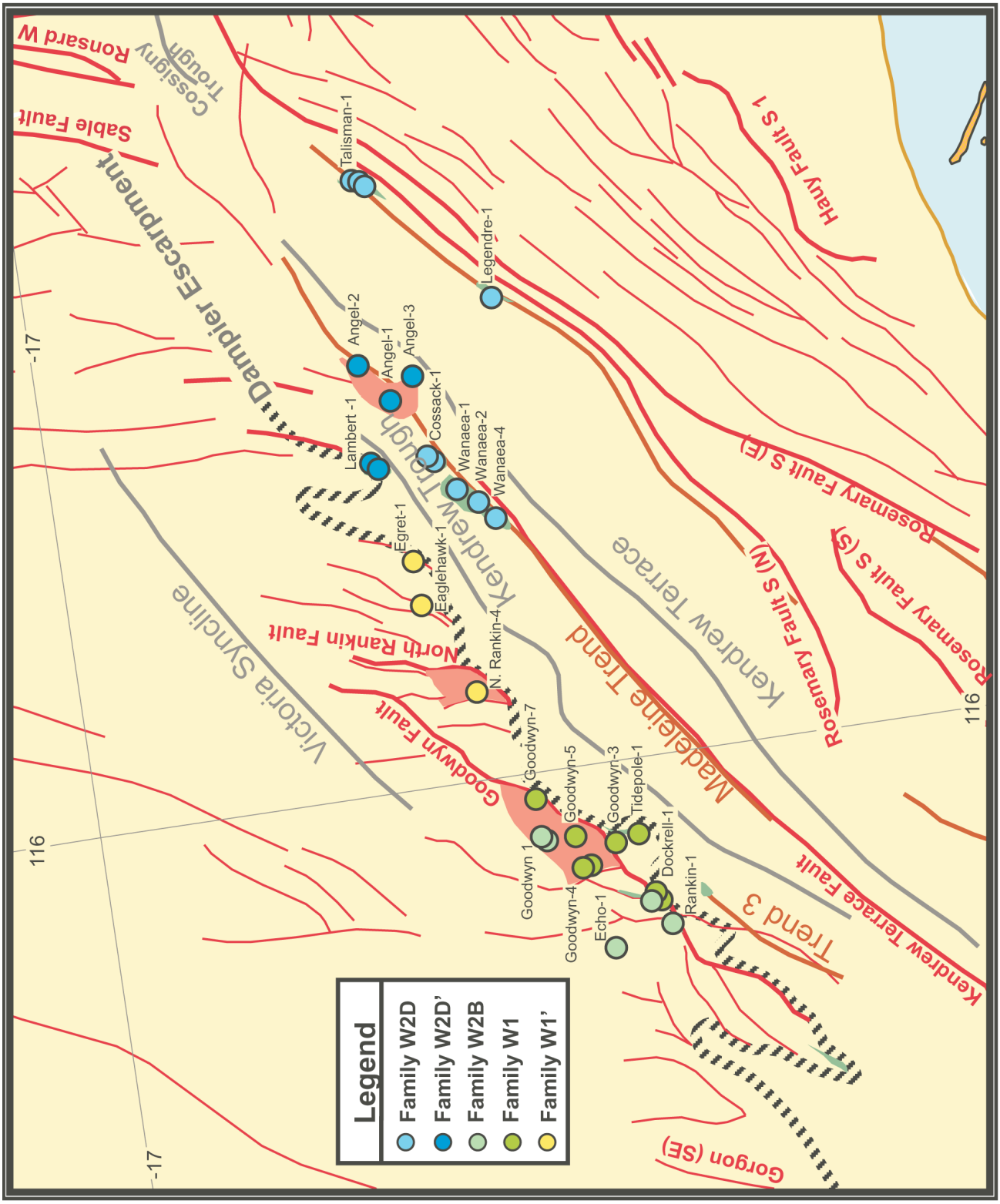


Figure IV-3. Map Showing Geographic Distribution of Dampier Sub-Basin Oil Families (see **Figure III-21** Dendrogram, p. III-45).

Jurassic-sourced with some Triassic input. However, the wide spectrum of maturities in this group of oils and condensates will also lead samples to 'wander' somewhat between similar families depending on what geochemical parameters are selected. The close genetic relationship of these oils and condensates confirms the productive nature of the Late Jurassic sediments of the Lewis Trough source kitchen. Confirmation that the Wandoo and Stag accumulations share this source would add to this status.

The Harriet and nearby Campbell, Rosette, Tanami and Bambra oils, located at the northern end of the Barrow Sub-basin (**Figure IV-4**) align themselves closely with the Dampier Family. This happens consistently, even when different combinations of biomarker and isotopic parameters are used for the statistical treatment. This likely reflects the extension of W2D, Late Jurassic restricted marine source facies, into the northern Barrow Sub-basin. Alternatively, a long-distance migration pathway along the Lowendal Fault system is another possibility which could be tested. Increasing maturities northwards from Harriet to Campbell and from Bambra to Rosette would be consistent with migration southwards since the earliest generated products are often found to have migrated the furthest. North Scott Reef, located far to the north in the Browse Basin, also falls in within the W2D Family. The Early to Middle Jurassic depocentre of possible marine facies, interpreted from the AGSO deep seismic coverage adjacent to the Scott Reef Trend (Symonds *et al*. 1994), is a possible source of these hydrocarbons. This depocentre may contain a similar organic facies to the restricted marine Late Jurassic sediments of the Lewis Trough, but being older and more mature. The geochemical analysis presented here, however, suggests an alternative, that is, the possible existence of undrilled pods of Late Jurassic (W2D) sediments adjacent to the Scott Reef Trend.

Burial history analysis conducted by the APS project team indicates that W2D sediments in the Dampier Sub-basin were generative from the Late Cretaceous and through most of the Cainozoic. In the Browse Basin, Jurassic sediments were probably generating optimally in the Late Cretaceous.

Family W2B Jurassic shales

Oils from the Barrow Sub-basin plot together in the Barrow Family (W2B; coloured light green). In this group are samples from Barrow, Chinook, Flinders Shoal, Hilda, North Herald, South Pepper and Saladin, (**Figure III-21**). They are interpreted as having been generated from Late Jurassic marine sediments, and with a possible additional contribution from Early Cretaceous deltaic facies, again belonging to the general Westralian Supersystem (Westralian 2). The differences with the Dampier Family could be explained by variations in the paleogeography of the two sub-basins since water depth and proximity to land would control organic matter quality and character.

Family W1; Triassic shales

A very tight correlation between Goodwyn, Dockrell and Tidepole oils (note that some Dockrell and Goodwyn oils have probable Jurassic affinities) and their geographic proximity in the Rankin Trend is seen as strong evidence for their common source.

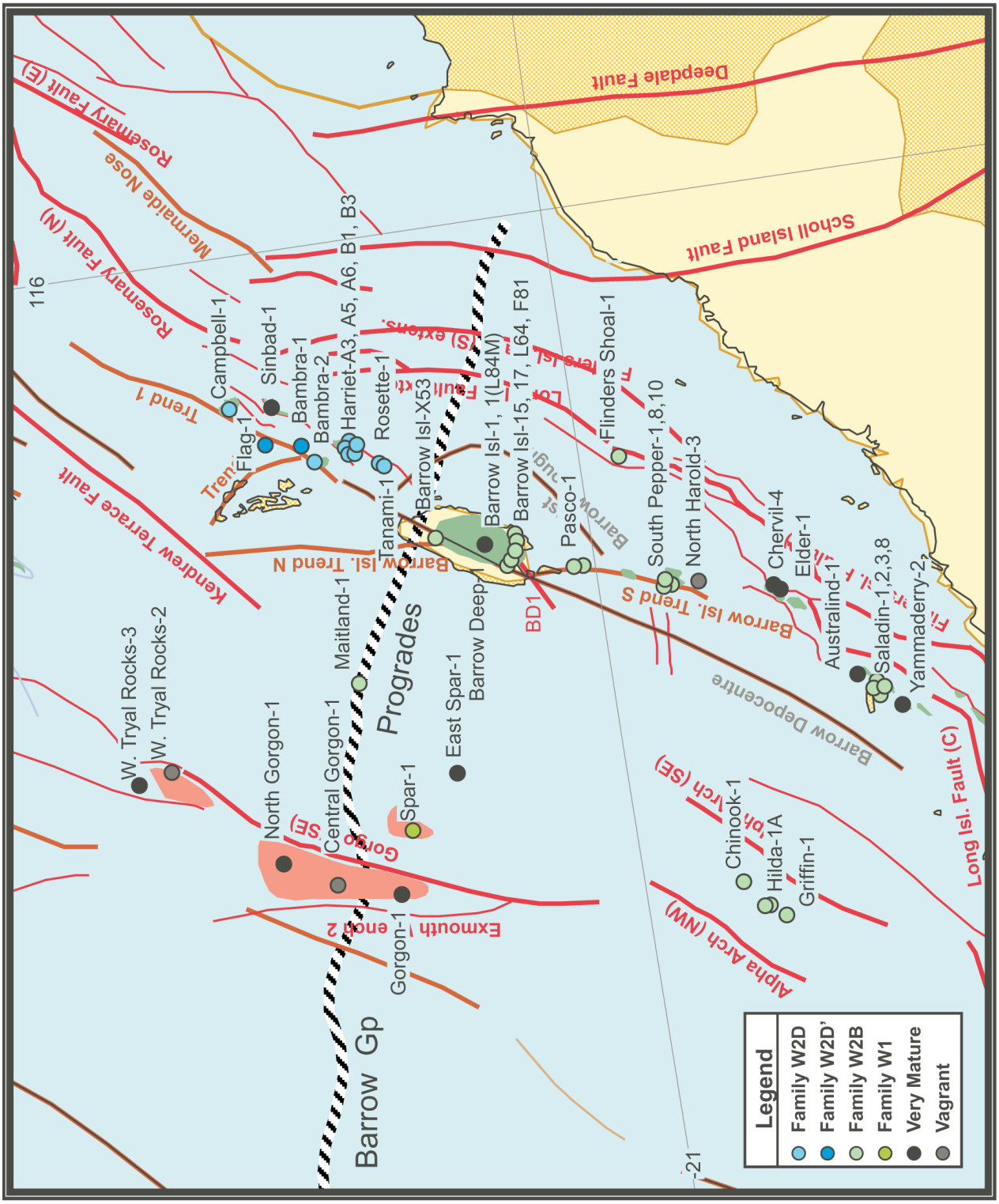


Figure IV-4. Map Showing Geographic Distribution of Barrow Sub-Basin Oil Families (see **Figure III-21** Dendrogram, p. III-45).

On geological grounds this common source appears to be in the underlying Triassic sediments of the Westralian (W1) petroleum system since Late Jurassic sediments are thin and not appropriately placed to source the gas, condensate and oil in these fields (e.g. Vincent and Tilburies, 1994). Spar to the south may share a similar source. This analysis then leads to the conclusion that Egret, Eaglehawk and a North Rankin-A condensate which fall together (here assigned as Family W1/W2), and which correlate poorly with the Goodwyn family, have a different origin or maturation regime. This could be within a different Jurassic (older?) source facies in the Kendrew Terrace adjacent to the Rankin Trend or possibly from a mixture of Jurassic and Triassic inputs from this depocentre.

Other points

Many of the Carnarvon Basin condensates had to be excluded from the statistical analysis discussed above because of their very low biomarker contents. When a limited set of variables, comprising Pr/Ph, Pr/*n*-C17 and isotope values were employed (data not shown), very loose clusters of condensates comprised East Spar, Sinbad, Elder, Barrow Deep, North Gorgon and Gorgon on one hand and West Tryal Rocks, Goodwyn-3, Flag, North Rankin-4, Central Gorgon, Maitland, North Herald and Chervil on the other. Such loose clusters can indicate heterogeneous source characteristics, mixed sources or alternatively, a variety of generation timing regimes. For example, Maitland, North Herald and Chervil could represent Family W2B late generation products from the Barrow depocentre. In the case of the West Tryal Rocks samples, a major contribution from an isotopically heavy Permian source is possible. Identification of source is further compromised by the obvious wide maturity spread of these samples. Other approaches to classification were tested, including an analysis of the light hydrocarbons (C7 isomers; Thompson 1983; Mango, 1987, 1994, BeMent, 1994), data which is provided with the study. However, no generally consistent trends about the origins of these condensates were immediately evident, possibly because the types of organofacies in the predominant W1 and W2 petroleum systems were somewhat similar. We intend to conduct detailed analyses of aromatic hydrocarbons in a future study to address this particular issue.

The Leatherback-1 oil plots as a ‘vagrant’ adjacent to the W2B Family (coloured pink). This may be because it is relatively immature. However, it may also indicate a further facies variation of the ubiquitous Late Jurassic source rock.

Finally the Nebo-1 oil from the Beagle Sub-basin shows strong chemical affinity to the Rough Range oils, and also to Gage Roads-1 in the Perth Basin. Biomarkers, isotopes and their waxy nature are all consistent with a non-marine source. These associations provide a compelling case to include them in a separate petroleum system, and this is designated Austral (A2).

Burial history analysis by the APS project team indicates vastly different timing regimes for different tectonic compartments of the Carnarvon Basin. For example, generation from W1 Triassic source rocks of the Barrow/Exmouth region likely reached its peak in the Late Jurassic and somewhat earlier further offshore on the Exmouth Plateau. The W2D petroleum system did not have the loading from the Barrow Delta and

was generative in the Late Cretaceous with a second phase late in the Cainozoic. Many of the high maturity condensates are likely to have been produced during this time. The demonstrated effectiveness of two Westralian petroleum systems (possibly of a third if one includes the Gondwanan) combined with multiple phases of generation increases the chances for appropriate timing of trap and charge. Cainozoic reactivation of earlier charged reservoirs, however, is a major exploration risk.

Canning Basin Oil Families

Family L2; Ordovician shales and carbonates

Three Canning Basin oil families are evident in the cluster analysis **Figure III-18**. Dodonea-1 and, to a lesser extent Pictor-1, show GC patterns in accord with Ordovician oils sourced world-wide by *G. prisca*. It is also likely that the Dodonea-1 oil is reservoired near to, or within its source horizon in the Goldwyer Formation (Hoffmann *et al*., 1987). Accordingly, the family is assigned as Larapintine 2 (Bradshaw *et al*., 1994).

Family L3; Devonian 'restricted' shales

The Blina and Janpam oils from the Lennard Shelf originate from a restricted marine (possibly hypersaline) calcareous shale source facies of the Larapintine 3 petroleum system (Devonian Gogo Formation and time equivalents).

Family L/G2; Carboniferous shales

A third family comprising Meda, Lloyd, West Terrace and Sundown oils were probably sourced from Early Carboniferous shales and show excellent internal correlation and, as was indicated by **Figure I-2**, correlate well with the Transitional L/G oils of the Petrel Sub-basin. The occurrence of several distinctive terpane biomarkers in the oils from both basins support this idea. The L3 and L/G oil families also have quite tight geographical associations (**Figure IV-5**)

Geohistory analysis of onshore wells across the Canning Basin (Kennard, 1995) indicate that the six Paleozoic source rocks attained peak maturity, generated and expelled the bulk of their hydrocarbons during major subsidence-sag phases in the Paleozoic and prior to the Fitzroy Transpression. Little or no generation has taken place since the Triassic. Seal integrity and the fact that significant structuring has taken place since peak generation times must be considered as a major exploration risks.

Perth Basin Oil Families

Family G1; Permian sediments

The Whicher Range-1 condensate is the sole representative of the Gondwanan 1 petroleum system in the Perth basin. It has the distinctive heavy carbon isotope signature of Permian petroleum and has affinities to the Petrel-4 (Petrel Sub-basin) and possibly the West Tryal Rocks and Barrow Deep (Carnarvon Basin) condensates.

Family G2; Triassic sediments

The largest group of Perth Basin oils also show the strongest geographical association in their distribution around the Dongara Saddle (**Figure IV-6**). These oils

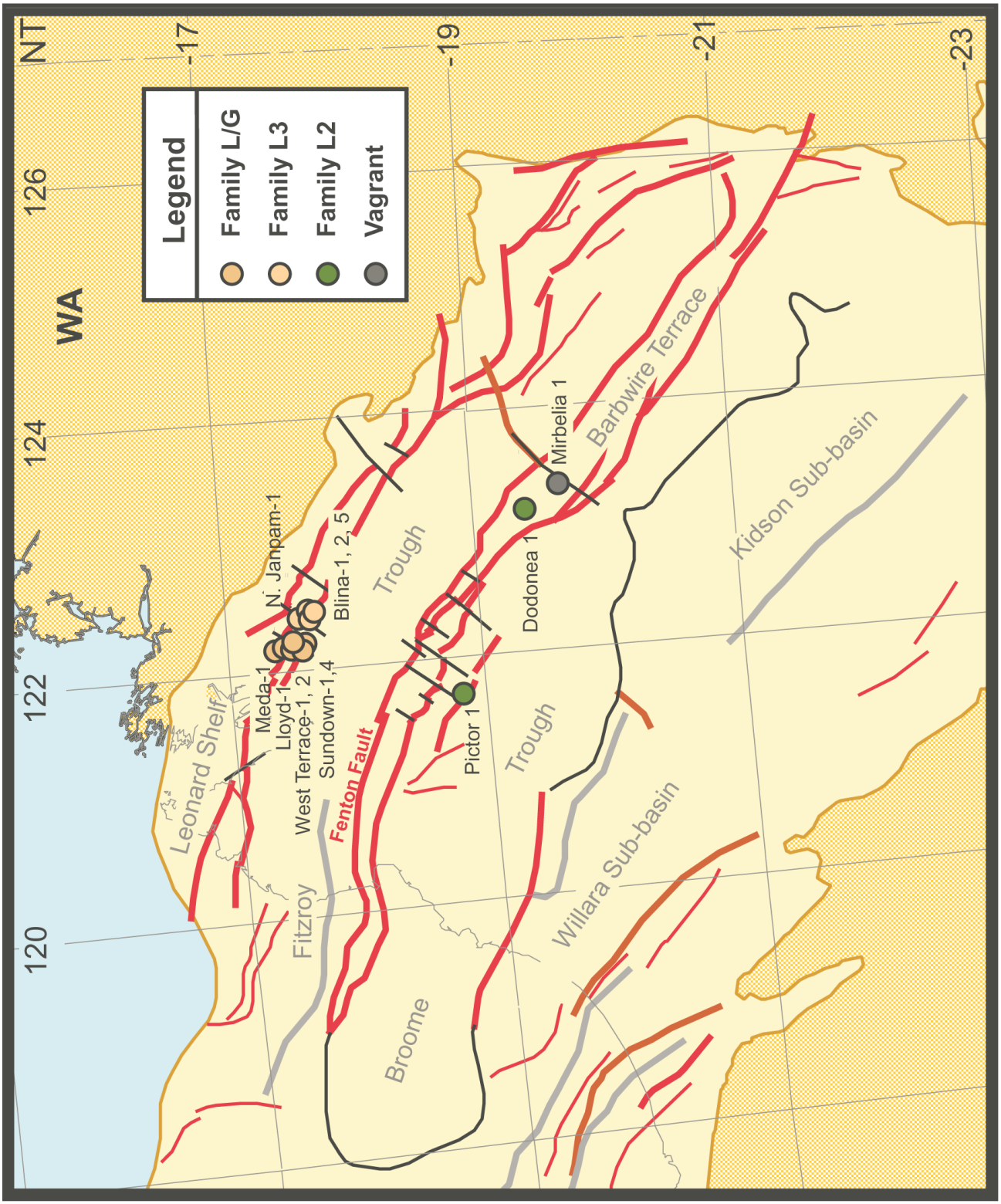


Figure IV-5. Map Showing Geographic Distribution of Canning Basin Oil Families (see **Figure III-18** Dendrogram, p. III-40).

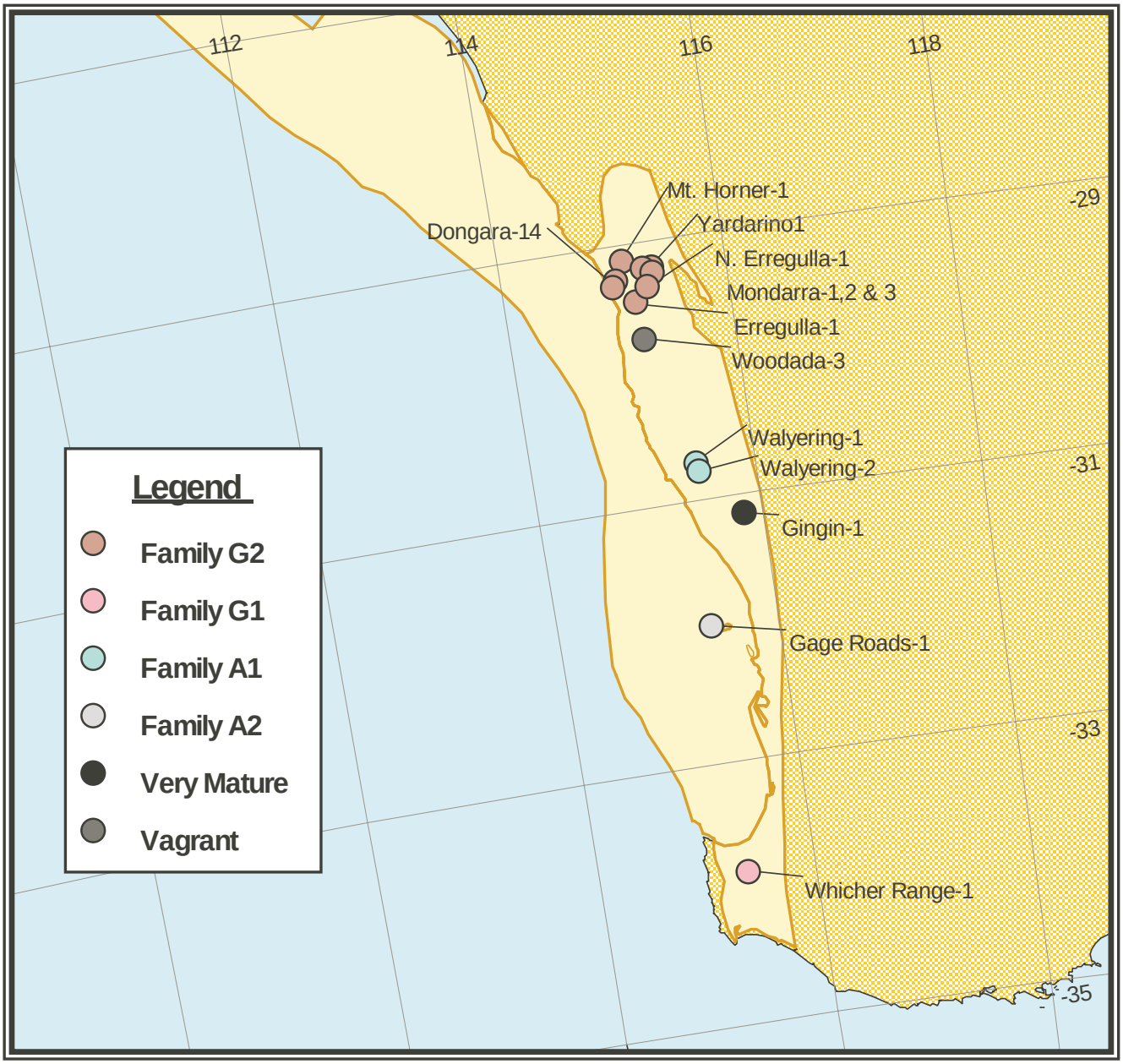


Figure IV-6. Map Showing Geographic Distribution of Perth Basin Oil Families (see **Figure III-25** Dendrogram, p. III-53).

have their source in the Early Triassic Kockatea shales of the Gondwanan (G2) petroleum system (e.g., Summons *et al*., 1995 and references therein). The most distinctive characteristic of these oils is an extremely light carbon isotopic signature. The source rock is exceptionally rich at its base. However, the thinness of this facies limits the volume of hydrocarbons that could have been generated and expelled.

Families A1 and A2; Jurassic and Cretaceous sediments

Walyering and Gingin condensates represent the Austral (A1) petroleum system sourced by deltaic shales while the Gage Roads-1 oil represents the A2 system with a lacustrine shale source. The volumetric extent of these sources limits the amount of hydrocarbons that could have been generated in this region, and this appears to be the major exploration risk in the basin.

Concluding Remarks

In summary, this study has exposed the existence of oil families not previously recognised for their wide geographic extent in west Australia basins. Notably, a family of lacustrine (A2) oils occurs widely in the Perth and Carnarvon Basins. Along with the occurrence of the Triassic-sourced Goodwyn and Dockrell oils (W1), this indicates that exploration should not be restricted to plays based on the Late Jurassic marine shales of the W2 petroleum system. An additional family of oils on the Sahul Platform, represented in this study by the Sunrise and Troubadour oils, exposes the existence of an effective 'dirty carbonate' source facies in the Timor Sea region. Permian-sourced condensate in the Petrel field, possible input of isotopically heavy, low molecular weight hydrocarbons to the Puffin oil, and isotopically heavy condensates at West Tryal Rocks-2, -3 and Barrow Deep-1 also suggest that Paleozoic sources should not be ruled out in exploration strategies. Paleobiodegradation is a feature of oils and condensates on the Rankin Trend, as it is in the Petrel Sub-basin. While this may seem to be a 'problem', particularly in the latter area, it also shows that there has been a long period, or multiple periods of reservoir charging. This allows for greater possibilities for optimal juxtaposition of trap and seal formation with respect to a charging pulse.

REFERENCES/BIBLIOGRAPHY

Archbold H. (1993). A zonation of the Permian brachiopod faunas of Western Australia. Gondwana 8, Balkema, Rotterdam, 313-321.

Backhouse J. (1984). Revised Late Jurassic and Early Cretaceous stratigraphy in the Perth Basin. Geol. Surv. WA Report #12 - Professional Papers for 1982, pp. 1-6.

Balme B.E. (1963). Plant microfossils from the Lower Triassic of Western Australia. *Palaeontology*, **6**, 12-40.

Balme B.E. (1968). Samples from Whicher Range No. 1 well. Palynology Report 290, pp. 1-41 (unpubl.).

Barber P.M. (1988). The Exmouth Plateau deep water frontier: a case history. In: *The North West Shelf, Australia* (Edited by Purcell, P.G. and Purcell, R.R.). Proceedings of the North West Shelf Symposium, PESA, Perth, 1988, pp. 173-187.

Barber P.M. (1994) Sequence stratigraphy and petroleum potential of Upper Jurassic-Lower Cretaceous depositional systems in the Dampier Sub-basin, North West Shelf, Australia. In: *The Sedimentary Basins of Western Australia* (Edited by Purcell P. G. and Purcell R.R.). Proceedings of the West Australian Basins Symposium, PESA, Perth, 1994, pp. 525-542.

Bentley J. (1988). The Candace Terrace-a geological perspective. In: *The North West Shelf, Australia* (Edited by Purcell P.G. and Purcell R.R.). Proceedings of the North West Shelf Symposium, PESA, Perth, 1988, pp. 157-171.

BeMent W.O., Levey R.A. and Mango F.D. (1994) The temperature of oil generation as defined with a C7 chemistry maturity parameter (2,4-DMP/2,3-DMP). AAPG/AMGP Hedberg Research Conference, October, 1994, Mexico City. Abstracts.

Blevin J.E., Stephenson A.E. and West B.G. (1993). The structural and stratigraphic framework of the Beagle Sub-basin - implications for hyrocarbon migration and trap development. *APEA Journal*, **33** (1), 105-122.

Blevin J.E., Stephenson A.E. and West B.G. (1994). Mesozoic structural development of the Beagle Sub-basin - implications for the petroleum potential of the northern Carnarvon Basin. In: *The Sedimentary Basins of Western Australia* (Edited by Purcell P.G. and Purcell R.R.). Proceedings of the West Australian Basins Symposium, PESA, Perth, 1994, pp. 479-496.

Blevin J.E., Colwell J.B., Edwards D.S., Foster C.B., Jones P. J., Kennard J.M., Nicoll R.S., O'Brien G.W., Shergold J.H., Summons R.E. and Wilson D.J. (1996a). Integrated

studies of the Petrel Sub-basin (Bonaparte Basin), defining the Palaeozoic foundations of the North West Shelf. Abstract, 13th Australian Geological Convention, February 1996.

Blevin J.E., Colwell J.B., Kennard J.M., Edwards D.S., Jones P.J., and Nicoll R.S. (1996b). Definition of basin phases in the Petrel Sub-basin (Australia): implications for the development of Palaeozoic Petroleum Systems. Abstract, AAPG Annual Convention, San Diego, June 1996.

Botten P. and Wulff K. (1990). Exploration potential of the Timor Gap Zone of Co-operation. *APEA Journal*, **30** (1), 68-90.

Bradshaw M. (1993). Australian petroleum systems. *PESA J.*, **21**, 43-53.

Bradshaw J. and Vizy J. (1990). Fission track database. BMR Record 1991/07.

Bradshaw M.T., Yeates A.N., Beynon R.M., Brakel A.T., Langford R.P., Totterdell J.M. and Yeung M. (1988). Palaeogeographic evolution of the North West Shelf region. In: *The North West Shelf, Australia* (Edited by Purcell P.G. and Purcell R.R.). Proceedings of the North West Shelf Symposium, PESA, Perth, 1988, pp. 29-54.

Bradshaw J., Vizy J., Blevin J., Edgecombe S. and Seggie R. (1992). Regional cross-sections of Australia. AGSO Record 1993/23.

Bradshaw M.T., Bradshaw J., Murray A.P., Needham D.J., Spencer L., Summons R.E., Wilmot J. and Winn S. (1994). Petroleum systems in western Australian basins. In: *The Sedimentary Basins of Western Australia* (Edited by Purcell P.G. and Purcell R.R.). Proceedings of the West Australian Basins Symposium, PESA, Perth, 1994, pp. 93-118.

Brakel A.T. and Totterdell J.M. (1990). The Permian palaeogeography of Australia. BMR Record 1990/60.

Burrett C., Long J. and Stait B. (1990). Early-Middle Palaeozoic biogeography of Asian terranes derived from Gondwana. In: *Palaeozoic Palaeogeography and Biogeography* (Edited by McFerrow W.S. and Scotese C.R.). Geological Society Memoir No. 12, pp. 163-174.

Clayton C.J. (1991). Effect of maturity on carbon isotope ratios of oils and condensates. *Org. Geochem.*, **17**, 887-99.

Clayton C.J. and Bjorøy M. (1994). Effect of maturity on $^{13}C/^{12}C$ ratios of individual compounds in North Sea oils. *Org. Geochem.*, **21**, 737-50.

Colwell J.B. and Stagg H.M.J. (1994). Structure of the offshore Canning Basin: first impressions from a new regional deep-seismic data set. In: *The Sedimentary Basins of*

Western Australia (Edited by Purcell P.G. and Purcell R.R.). Proceedings of the West Australian Basins Symposium, PESA, Perth, 1994, pp. 757-767.

Dowling L.M., Boreham C.J., Hope J.M., Murray A.P. and Summons R.E. (1995) Carbon isotopic composition of hydrocarbons in ocean-transported bitumens from the coastline of Australia. *Org. Geochem.*, **23**, 729-737.

Durrant J.M., France R.E., Dauzacker M.V. and Nilsen T. (1990). The southern Bonaparte Gulf - new plays. *APEA Journal*, **31** (1), 52-67.

Elliot R.M.L. (1990). Browse Basin. In: *The Geology and Mineral Resources of Western Australia.* Western Australia Geological Survey, Memoir 3, pp. 535-547.

Etheridge M.A, Symonds P.A. and Powell T.G. (1988) Application of the detachment model for continental extension to hydrocarbon exploration in extensional basins. *APEA Journal*, **28** (1), 167-187.

Etheridge M.A., Lister G.A. and Symonds P.A. (1990), Application of the detachment model to reconstruction of conjugate passive margins. AAPG Memoir, **46**, 23-40.

Etheridge M.A. and O'Brien G.W. (1994). Structural and tectonic evolution of the western Australian margin basin system. *PESA J.*, No. **22**, 45-63.

Etheridge M.A. and Wall V.J. (1994). Tectonic and structural evolution of the Australian Proterozoic (extended abstract). 12th Australian Geological Convention.

Fittall A.M. and Cowley R.G. (1992). The HV11 3-D seismic survey: Skua-Swift area geology revealed? *APEA Journal*, **32** (1), 159-170.

Freeman K.H. (1991) The carbon isotopic compositions of individual compounds from ancient and modern depositional environments. Ph.D. Thesis, University of Indiana, Bloomington (unpublished).

Gorter J. D., Foster C.B. and Summons R.E. (1996). Carbon isotopes and the Permian-Triassic boundary in the north Perth, Bonaparte and Carnarvon Basins, Western Australia. *PESA J.*, No. **23**, 21-38.

Grantham P. and Wakefield L. (1988). Variations in the sterane carbon number distributions of marine source rock derived crude oils through geological time. *Org. Geochem.*, **12**, 61-73.

ten Haven H.L. (1995) Application and limitations of Mango's light hydrocarbon parameters in petroleum correlation studies. Abstr. 17th International Mtg. on Organic Geochemistry, San Sebastian, Sept. 1995, pp. 1075-1077. . *Org. Geochem.* in press.

Hayes J.M. (1993). Factors controlling ^{13}C contents of sedimentary organic compounds: principles and evidence. *Marine Geology*, **113**, 111-25.

Hill G. (1994). The role of the pre-drift structure in the architecture of the Dampier Basin area, North West Shelf, Australia. *APEA Journal*, **34** (1), 602-613.

Hocking R.M. (1988). Regional geology of the northern Carnarvon Basin. In: *The North West Shelf, Australia* (Edited by Purcell P.G. and Purcell R.R.). Proceedings of the North West Shelf Symposium, PESA, Perth, 1988, pp. 97-114.

Hocking R.M., Mory A.J. and Williams I.R. (1994). An atlas of Neoproterozoic and Phanerozoic basins of Western Australia. In: *The Sedimentary Basins of Western Australia* (Edited by Purcell P.G. and Purcell R.R.). Proceedings of the West Australian Basins Symposium, PESA, Perth, 1994, pp. 21-43.

Hoffmann C.F., Foster C.B., Powell T.G. and Summons R.E. (1987) Hydrocarbon biomarkers from Ordovician sediments and the fossil alga Gloeocapsomorpha prisca Zalessky 1917. *Geochim. Cosmochim. Acta*, **51**, 2681-2697.

Jackson M.J., Diekman L.J., Kennard J.M., Southgate P.N., O'Brien P.E. and Sexton M.J. (1992). Sequence stratigraphy, basin-floor fans and petroleum plays in the Devonian-Carboniferous of the northern Canning Basin. *APEA Journal*, **32** (1), 214-230.

James A.T. (1990). Correlation of reservoired gases using the carbon isotopic compositions of wet gas components. *AAPG Bulletin*, **74**, 1441-58.

Jefferies P.J. (1984). Petroleum geochemistry of the northern Perth Basin. Postgraduate Diploma Report, Western Australian Institute of Technology (unpubl.).

Kantsler A.J. and Cook A.C. (1979). Maturation patterns in the Perth Basin. *APEA Journal*, **19** (1), 94-107.

Kennard J.M. (1995). Preservation of ld accumulations - key to Canning Basin exploration. *AGSO Research Newsletter*, **22**, 5-7.

Kennard J.M., Jackson M.J., Romine K.K., Shaw R.D. and Southgate P.N. (1994). Depositional sequences and associated petroleum systems of the Canning Basin, WA. In: *The Sedimentary Basins of Western Australia* (Edited by Purcell P.G. and Purcell R.R.). Proceedings of the West Australian Basins Symposium, PESA, Perth, 1994, pp. 657-676.

Klemme H.D. and Ulmishek G.F. (1991). Effective petroleum source rocks of the world: stratigraphic distribution and controlling depositional factors. *AAPG Bull.*, **75**, 1809-1851.

Knoll A.H., Hayes J.M., Kaufmann A.J., Swett K. and Lambert I.B. (1986). Secular variation in carbon isotope ratios from Upper Proterozoic successions of Svalbad and East Greenland. *Nature*, **321**, 832-838.

Kopsen E. and McGann G. (1985). A review of the hydrocarbon habitat of the eastern and central Barrow-Dampier Sub-basin, Western Australia. *APEA Journal*, **25** (1), 154-176.

Lee R.J. and Gunn P.J. (1988). The Bonaparte Basin. In: *Petroleum in Australia: The First Century* (Edited by Parry J.C. and Smith D.N.), pp. 252-268. Australian Petroleum Exploration Association, Sydney.

Li X. (1986). The mixed Permian Cathysia-Gondwana flora. *Palaeobotany*, **35** (2), 211-222.

Lisk M. and Eadington P. (1994). Oil migration in the Cartier Trough, Vulcan Sub-basin. In: *The Sedimentary Basins of Western Australia* (Edited by Purcell P.G. and Purcell R.R.). Proceedings of the West Australian Basins Symposium, PESA, Perth, 1994, pp. 301-312.

Lister G.S., Etheridge M.A. and Symonds P.A. (1991). Detachment models for the formation of passive continental margins. *Tectonics*, **10**, 1038-64.

Magaritz M., Krishnamurthy R.V. and Holser W.T. (1992). Parallel trends in organic and inorganic carbon isotopes across the Permian/Triassic boundary. *Am. J. Sci.*, **292**, 727-39.

McConachie B.A., Bradshaw M.T., Edgecombe S., Evans. D., Foster C.B., Bradshaw J., Nicoll R.S. and Jones P.J. (1995). Australian Petroleum Systems-Petrel Sub-basin Module. AGSO Record 1995/7, vol. 1-3.

McConachie B.A., Bradshaw M.T. and Bradshaw J. (1996). Petroleum systems of the Petrel Sub-basin - an integrated approach to basin analysis and identification of hydrocarbon exploration opportunities. *Aust. Pet. Prod. Explor. Assoc. J.* (in press).

MacDaniel R.P. (1988). The geological evolution and hydrocarbon potential of the western Timor Sea region. In: *Petroleum in Australia: The First Century* (Edited by Parry J.C. and Smith D.N.), pp. 270-284. Australian Petroleum Exploration Association, Sydney.

Mackenzie A.S. (1984). Applications of biological markers in petroleum geochemistry, In: *Advances in Petroleum Geochemistry Vol. I*, (Edited by Brooks J. and Welte D.) Academic Press, New York, pp. 115-214.

McTavis R.A. and Dickins J.M. (1974). The age of the Kockatea Shale (Lower Triassic) - a reassessment. *J. Geol. Soc. Aust.*, **21**, 195-202.

Malcolm R.J., Pott M.C. and Delfos E. (1991). A new tectono-stratigraphic synthesis of the North West Cape area. *APEA Journal* , **32** (1), 154-176.

Mango F.D. (1987) An invariance in the isoheptanes of petroleum. *Science*, **237**, 514-517.

Mango F.D. (1994) The origin of light hydrocarbons in petroleum: Ring preference in the closure of carbocyclic rings. *Geochim. Cosmochim. Acta* **58**, 895-901.

Maung T.U., Cadman S. and West B.G. (1994) A review of the petroleum potential of the Browse Basin. In: *The North West Shelf, Australia* (Edited by Purcell P.G. and Purcell R.R.). Proceedings of the North West Shelf Symposium, PESA, Perth, 1988, pp. 333-346.

Merritt D.A., Brand W.A and Hayes J.M. (1994) Isotope-ratio-monitoring gas chromatography-mass spectrometry: methods for isotopic calibration. *Org. Geochem.*, **21**, 573-83.

Metcalfe I. (1986). Late Palaeozoic palaeography of Southeast Asia: some stratigraphical, palaeontological and palaeomagnetic constraints. *GEOSEA, vol 1*. Proceedings of the Geological Society of Malaysia, Bulletin 19, 153-164.

Moldowan J.M., Seifert W.K. and Gallegos E.J. (1985). Relationship between petroleum composition and depositional environment of petroleum source rocks. *AAPG Bulletin*, **69**, 1255-1268.

Morante R., Veever J.J., Andrew A.S. and Hamilton P.J. (1994) Determination of the Permian-Triassic boundary in Australia from carbon isotope stratigraphy. *APEA Journal*, **34**, 330-6.

Mory A.J. (1988). Regional geology of the offshore Bonaparte Basin. In: *The North West Shelf, Australia* (Edited by Purcell P.G. and Purcell R.R.). Proceedings of the North West Shelf Symposium, PESA, Perth, 1988, pp. 278-307.

Mory A.J. (1990). Bonaparte Basin. In: *Geology and Mineral Resources of Western Australia*, Western Australia Geological Survey, Memoir 3, 380-415.

Mory A.J. and Iasky R.P. (1994). Structural evolution of the onshore northern Perth Basin, Western Australia. In: *The Sedimentary Basins of Western Australia* (Edited by Purcell P.G. and Purcell R.R.). Proceedings of the West Australian Basins Symposium, PESA, Perth, 1994, pp. 781-789.

Nelson A.W. (1989). Jabiru Field - horst, sub-horst of inverted graben? *APEA Journal*, **29** (1), 176-194.

Nelson A. (1993). Wrench and inversion structures in the Timor Sea region *PESA J.*, **21**, 3-30.

Nicoll R.S., Owen M., Shergold J.H., Laurie J.R. and Gorter J.D. (1988). Ordovician event stratigraphy and the development of the Larapintine Seaway, central Australia. *BMR Record 1988/42*, pp. 72-77.

O'Brien G.W. (1993). Some ideas on the rifting history of the Timor Sea from the integration of deep crustal seismic and other data. The PESA Australian Lecture 1992, *PESA J.*, **21**, 95-113.

O'Brien G.W. and Woods E.P. (1994).Vulcan Sub-basin, Timor Sea: cluse to the structural reactivation and migration history from the recognition of hydrocarbon seep indicators. AGSO Research Newsletter, **21**, 8-11.

O'Brien G.W. and Lisk M. (1995) Determination of hydrocarbon charge history and trap integrity from the recognition of hydrocarbon-related diagenetic zones on the North-West Shelf. Abstracts of the Australian Organic Geochemists Conference, Adelaide University, Adelaide, SA.

O'Brien G.W. and Woods E.P. (1995). Hydrocarbon-related diagenetic zones (HRDZs) in the Vulcan Sub-basin, Timor Sea: recognition and exploration implications. *APEA Journal*, **35** (1), 220-252.

O'Brien G.W., Etheridge M.A., Willcox J.B., Morse M., Symonds P., Norman C. and Needham J.D. (1993). The structural architecture of the Timor Sea, north-western Australia: implications for basin development and hydrocarbon exploration. *APEA Journal*, **33** (1), 258-278.

O'Brien G.W., Blevin J., Gunn P., Romine K., Scott D.L., Wilxox J.B. and Baldwin S. (1995). The Petrel Sub-basin, Timor Sea, Australia: Rift architecture and its control on structuring within the Mesozoic and Tertiary sequence, Timor Sea. Abstr. AAPG Annual Convention, Houston, 1995.

O'Brien G.W., Lisk M., Duddy I., Eadington P.J., Cadman S. and Fellows M. (1996). Late Tertiary fluid migration in the Timor Sea: a key control on thermal maturity and diagenetic histories? APPEA Journal, (in press).

O'Brien G.W., Higgins R., Quaife P., Symonds P., Blevin J. and Colwell J. (1996).A hybrid hard-lik/soft link fault model for the developments of extensional basins: The death knell for the transfer fault? APPEA Journal, (in press).

Osborne D.G. (1994). Nebo oil discovery, Beagle Sub-basin. In: *The Sedimentary Basins of Western Australia* (Edited by Purcell P.G. and Purcell R.R.). Proceedings of the West Australian Basins Symposium, PESA, Perth, 1994, pp. 653-654.

Osborne M. (1990). The exploration and appraisal history of the Skua Field, AC/P2 - Timor Sea. *APEA Journal*, **30** (1), 197-211.

Parry J.C. and Smith D.N. (1988). The Barrow and Exmouth Sub-basins. In: *The North West Shelf Australia* (Edited by Purcell P.G. and Purcell R.R.). Proceedings of the North West Shelf Symposium, PESA, Perth, 1988, pp. 129-145.

Pattillo J. and Nicholls P.J. (1990). A tectonostratigraphic framework for the Vulcan Graben, Timor Sea Region. *APEA Journal*, **30** (1), 27-51.

Peters K., Moldowan J.M., Schoell M. and Hempkins W.B. (1986). Petroleum isotopic and biomarker composition related to source rock organic matter and depositional environment. *Org. Geochem.*, **10**, 17-27.

Peters K. and Moldowan J.M. (1993). *The Biomarker Guide*, Prentice Hall, New York, 352 pp.

Playford P.E. (1984). Platform margin and marginal-slope relationships in Devonian reef complexes of the Canning Basin. In*: The Canning Basin W.A.* (Edited by Purcell, P. G.). Proceedings of the Canning Basin Symposium, GSA/PESA, Perth, 1984, pp. 189-214.

Powell T.G. and McKirdy D.M. (1973a). Relationship between ratio of pristane to phytane, crude oil composition and geological environment in Australia. *Nature*, **243**, 37-39.

Powell T.G. and McKirdy D.M. (1973b). Crude oil correlations in the Perth and Carnarvon Basins. *APEA Journal*, **13** (1), 81-85.

Powell T.G. and McKirdy D.M. (1975). Geological factors controlling crude oil composition in Australia and Papua, New Guinea. *AAPG Bulletin*, **59** (7), 1176-1197.

Schoell M. (1983). Genetic characterisation of natural gases. *AAPG Bulletin*, **67**, 2225-38.

Scott J. (1992). Accurate recognition of source rock character in the Jurassic of the North West Shelf, Western Australia. *APEA Journal*, **32** (1), 289-299.

Scott J. (1994). Source rocks of Western Australia - distribution, character and models. In: *The Sedimentary Basins of Western Australia* (Edited by Purcell P.G. and Purcell R.R.). Proceedings of the West Australian Basins Symposium, PESA, Perth, 1994, pp. 141-155.

Seifert W.K. and Moldowan J.M. (1981). Paleoreconstruction by biological markers. *Geochim. Cosmochim. Acta*, **45**, 783-794.

Seifert W.K., Moldowan J.M. and Demaison G.J. (1984). Source correlation of biodegraded oils. *Org. Geochem.*, **6**, 633-643.

Sinninghe Damste J.S., Kenig F., Koopmans M.P., Koster J., Schouten S., Hayes J.M., and de Leeuw J.W. (1995). Evidence for gammacerane as an indicator of water column stratification. *Geochim. Cosmochim. Acta*, **59**, 1895-1900.

Sofer Z. (1980). Preparation of carbon dioxide for stable carbon isotope analysis of petroleum fractions. *Anal. Chem.*, **52**, 1389-1391.

Sofer Z. (1984). Stable carbon isotope compositions of crude oils: Application to source depositional environments and petroleum alteration.*AAPG Bulletin*, **68**, 31-49.

Spencer L., Sayers J., Bradshaw J., Bradshaw M., Foster C.B., Murray A., Edwards D., Zuccaro G., Buchanan C. and Apps H. (1995). Exmouth Plateau and Outer Rankin Platform Module. AGSO Record 1995/80, vol. 1.

Spring D.E. and Newell N.A. (1993) Depositional systems and sequence stratigraphy of the Cretaceous Warnbro Group, Vlaming Sub-basin, Western Australia. APEA Journal, **33** (1), 190-204.

Stagg H.M.J. and Colwell J.B. (1994). The structural foundation of the northern Carnarvon Basin. In: *The Sedimentary Basins of Western Australia* (Edited by Purcell P.G. and Purcell R.R.). Proceedings of the West Australian Basins Symposium, PESA, Perth, 1994, pp. 349-364.

Summons R.E., Boreham C.J., Foster C.B., Murray A.M. and Gorter J.D. (1995). Chemostratigraphy and the composition of oils in the Perth Basin, Western Australia. *APEA Journal*, **35** (1), 613-632.

Symonds P.A., Collins C.D.N. and Bradshaw J. (1994). Deep structure of the Browse Basin: implications for basin development and petroleum exploration. In: *The Sedimentary Basins of Western Australia* (Edited by Purcell P.G. and Purcell R.R.). Proceedings of the West Australian Basins Symposium, PESA, Perth, 1994, pp. 315-331.

Teichert C. (1939). The Mesozoic transgressions in Western Australia. *Aust. J. Earth Sci.*, **2**, 84-86.

Teichert C. (1951). The marine Permian faunas of Western Australia. *Zeitschrift fur Palaeontologie*, **24**, 76-90.

Thomas B.M. (1979). Geochemical analysis of hydrocarbon occurrences in northern Perth Basin, Australia. *AAPG Bulletin*, **63** (7), 1092-1107.

Thomas B.M. (1982). Land-plant source rocks for oil and their significance in Australian basins. *APEA Journal*, **22** (1), 164-177.

Thomas B.M. and Brown S.A. (1983). Hydrocarbon generation in the northern Perth Basin. *APEA Journal*, **23** (1), 64-74.

Thompson K.F.M. (1983) Classification and thermal history of petroleum based on light hydrocarbons. *Geochim. Cosmochim. Acta* **47**, 303-316.

Tissot B.P. and Welte D.H. (1984). *Petroleum Formation and Occurrence*, 2nd edn., Springer, Berlin.

Tupper N.P., Phillips S.E. and Williams B.P.J. (1994). Advances in the understanding of upper Permian reservoir distribution and quality, north Perth Basin. In: *The Sedimentary Basins of Western Australia* (Edited by Purcell P.G. and Purcell R.R.). Proceedings of the West Australian Basins Symposium, PESA, Perth, 1994, pp. 823-837.

Veevers J.J. (1984). *Phanerozoic Earth History of Australia*. Oxford University Press.

Veevers J.J., Powell C.M. and Roots S.R. (1991). Review of seafloor spreading around Australia. I. Synthesis of the patterns of spreading. *Aust. J. Earth Sci.*, **38**, 391-408.

Vincent P. & Tilbury L., 1988 - Gas and oil fields of the Rankin Trend and northern Barrow-Dampier Sub-basin. In Purcell P.G. & Purcell R.R. (Eds), *The North West Shelf, Australia*, Proceedings of Petroleum Exploration Society Australia Symposium, Perth, 1988, 341-369.

Warris B.J. (1973). Plate tectonics and the evolution of the Timor Sea, northwest Australia. *APEA Journal*, **13** (1), 13-18.

Warris B.J. (1993). The hydrocarbon potential of the Palaeozoic basins of Western Australia. *APEA Journal*, **33** (1), 123-137.

West N., Alexander R. and Kagi R.I. (1990). The use of silicalite for rapid isolation of branched and cyclic alkane fractions of petroleum. *Org. Geochem.* **15**, 499-501.

Woods E.P. (1988). Extensional structures of the Jabiru Terrace, Vulcan Sub-basin. In: *The North West Shelf Australia* (Edited by Purcell P.G. and Purcell R.R.). Proceedings of the North West Shelf Symposium, PESA, Perth, 1988, pp. 311-330.

Woods E.P. (1992). Vulcan Sub-basin fault styles - implications for hydrocarbon migration and entrapment. *APEA Journal*, **32** (1), 138-158.

Woodside Offshore Petroleum Pty. Ltd. (1988). A review of the petroleum geology and hydrocarbon potential of the Barrow-Dampier Sub-basin and environs. In: *The North*

West Shelf, Australia (Edited by Purcell P.G. and Purcell R.R). Proceedings of the North West Shelf Symposium, PESA, Perth, 1988, pp. 115-128.

Yeates A.N., Bradshaw M.T., Dickens J.M., Brakel A.T., Exon N.F., Langford R.P., Mulholland S.M., Totterdell J.M. and Yeung M. (1987). The Westralian Superbasin: an Australian link with Tethys. In: *Proceedings, Second Shallow Tethys Conference* (Edited by McKenzie K.G.), pp. 199-214. A.A. Balkema, Wagga Wagga, NSW, Australia.

Zumberge J.E. (1984). Source rocks of the La Luna Formation (Upper Cretaceous) in the Middle Magdalena Valley, Colombia. In: *Petroleum Geochemistry and Source Rock Potential of Carbonate Rocks*. (edited by Palacas J.G.) AAPG Studies in Geology #18, pp. 127-133.

Zumberge J.E. (1987a). Terpenoid biomarker distributions in low maturity crude oils. *Org. Geochem.*, **11**,479-496.

Zumberge J.E. (1987b). Prediction of source rock characteristics based on terpane biomarkers in crude oils: a multivariate statistical approach. *Geochim. Cosmochim. Acta*, **51**, 1625-1637.

EXPERIMENTAL PROCEDURES

Liquid Chromatographic Separation

Subsequent to determining the <C15 fraction (light ends) by evaporation in a stream of nitrogen for 30 min, and asphaltene precipitation by flooding with n-hexane or petroleum ether and standing overnight at room temperature, the C15+ deasphalted fractions were separated into saturate hydrocarbon, aromatic hydrocarbon, and NSO (nitrogen-sulfur-oxygen compounds or resin) fractions using gravity-flow column chromatography employing a 100-200 mesh silica gel support activated at 400° C prior to use. Petroleum ether was used to elute the saturate hydrocarbons, 1:1 dichloromethane/petroleum ether to elute the aromatic hydrocarbons, and methylene chloride/methanol (50:50) to elute the NSO fraction. Following solvent evaporation, the recovered fractions were quantified gravimetrically. The C15+ saturate hydrocarbon fraction in pentane was subjected to molecular sieve filtration (Silicalite i.e. Union Carbide S-115 powder) after the technique described by West *et al.* (1990) in order to concentrate the branched/cyclic biomarker fraction (SNA).

Stable Isotope Analyses

Stable carbon isotopic compositions ($^{13}C/^{12}C$) of the C15+ saturate and aromatic hydrocarbon fractions were determined using the combustion technique of Sofer (1980) and a Finnigan Delta E isotope ratio mass spectrometer. Results are reported relative to the PDB standard.

GC/FID of Whole Oils

The analysis was conducted using a Varian 3400 Gas Chromatograph fitted with an HP 50 m x .22mm id fused silica methyl silicone bonded phase thick phase HP-1 (Pona) column. The carrier gas was H_2 at 20 psi with an initial flow rate of H_2 is 150 mL/min. The temperature program was: 30° C for 20 min hold , then 8° C/min ramp rate to 310° C. Hold final temperature for 40 min to have a total run time of 90 min. Injection was via a temperature programmable on-column injector at 300°C.

Gas Chromatography/Mass Spectroscopy (GC/MS)

GC/MS analyses of C15+ branched/cyclic hydrocarbon fractions (in order to determine sterane and terpane biomarker distributions and quantities) were performed using a Hewlett Packard (HP) 5890 GC (split injection) interfaced to a HP 5971 mass spectrometer. The HP-2 column (50 m x 0.2 mm; 0.11 µm film thickness) was temperature programmed from 150° C to 325° C at 2°/min and then held for 10 min. The mass spectrometer was run in the selected ion mode (SIM), monitoring ions m/z 177, 191, 205, 217, 218, 221, 231, and 259 amu. In order to determine absolute concentrations of individual biomarkers, a deuterated internal standard (d_4-C29 20R sterane; Chiron Laboratories, Norway) was added to the C15+ branched/cyclic hydrocarbon fraction. Response factors (RF) were determined by comparing the mass spectral response at m/z 221 for the deuterated standard to hopane (m/z 191) and sterane (m/z 217) authentic standards. These response factors were found to be approximately 1.4 for terpanes and 1.0 for steranes. Concentrations of individual biomarkers were determined using the

equation shown below:

Conc.(ppm) = (Area biomarker)(ng standard)/(Area standard)(RF)(mg b/c fraction).

Analysis of silicalite-non-adducts (SNA) by Gas Chromatography-Mass Spectrometry: Multiple Reaction Monitoring (MRM) mode

Prior to injection, 100 µL limited volume inserts were placed in GC vials and 100 ng of d_4-ααα-ethyl cholestane 20R in hexane was added as an internal standard. SNA fractions were diluted to 1 mg/100 µg of hexane and 100 µL of sample was inserted into the vial. Hence the total fraction was at a 1:100 dilution.

The instrument comprised a Carlo Erba GC fitted with using a CTC autosampler. Injection was 1-2ml in splitless mode at 270°C. The column was a 50m x .22 mm id fused silica crosslinked methyl silicone HP Ultra-1 column and programmed from an initial temperature of 50°C held for 2 mins and then to 180° C at 10° C /min then to 310° C at 3° C /min. Final temperature held for 20 mins. Carrier gas was H_2 at 20 psi and a linear flow of approximately 30 cm/sec. Interface temperature was 310° C.

The mass spectrometer was a VG Ultima-Q hybrid instrument. Diagnostic parent-daughter ions were observed by monitoring spontaneous FFR-1 decomposition and representing various tricyclic and diterpane compounds (function 1) as well as ions representing various biomarkers (function 2).

Function 1

High mass:	360.4
Low mass:	208.2
Resolution:	800
Ionisation Mode:	EI+
Accelerating Voltage	8000 V
Magnet 1 Control	Field
Start Time:	10:00
End Time:	47:30
Number of Channels	13
Cycle Time:	1220ms

Channel	Parent Mass	Daughter Mass	Ch Time (ms)	I/ch Time (ms)
1	262.2650	191.1790	40	100
2	276.2800	191.1790	40	50
3	290.2960	191.1790	40	50
4	304.3120	191.1790	40	50
5	318.3280	191.1790	40	50
6	330.3280	191.1790	40	50
7	332.3440	191.1790	40	50
8	346.3590	191.1790	40	50
9	360.3740	191.1790	40	50
10	208.2200	137.1320	40	50
11	208.2200	123.1170	40	50
12	222.2350	123.1170	40	50
13	274.2650	123.1170	40	50

Function 2

High mass:	482.5
Low mass:	370.4
Resolution:	800
Ionisation Mode:	EI+
Accelerating Voltage	8000 V
Magnet 1 Control	Field
Start Time:	47:30
End Time:	80:00
Number of Channels	19
Cycle Time:	1890 ms

Channel	Parent Mass	Daughter Mass	Ch Time (ms)	I/ch Time (ms)
1	426.4210	383.3676	40	80
2	421.4060	369.3520	40	50
3	389.4105	234.2320	40	200
4	414.4230	231.2120	40	60
5	372.3760	217.1960	40	50
6	386.3910	217.1960	40	50
7	404.4321	221.2210	40	50
8	400.4070	217.1960	40	50
9	414.4230	217.1960	40	50
10	426.4210	205.1940	40	50
11	370.3590	191.1790	40	40
12	384.3740	191.1790	40	50
13	398.3900	191.1790	40	50
14	412.4060	191.1790	40	50
15	426.4210	191.1790	40	50
16	398.3900	177.1640	40	50
17	468.4670	191.1790	40	50
18	412.4060	177.1640	40	50
19	482.4820	191.1790	40	50

Data was captured and processed by OPUS software.

Compound Specific Isotope Analysis of *n*-alkanes

Carbon isotopic determinations for individual petroleum hydrocarbons were carried out using gas chromatography-combustion-isotope ratio mass spectrometry (GC-C-IRMS) as described by Freeman (1991), Merritt *et al*. (1994) and Dowling *et al*. (1995). Calibration was via CO_2 standards introduced with a changeover valve and verified using co-injected deuterated *n*-alkane standards. Our analyses of a C_{12}-C_{39} *n*-alkane standard gives δ-values within 0.3 ‰ of nominal values. Isotopic analysis of *n*-alkanes was made using a fraction prepared by adduction from whole oil or saturated hydrocarbons into Linde 5Å sieve in refluxing toluene. Toluene-washed sieve was covered with *n*-pentane prior to alkanes being released by addition of hydrofluoric acid.

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APPENDIX A

Bulk and Gas Chromatographic Data

BULK.XLS

SampleID	API	<C15	% S	ppm Ni	ppm V	% Sat	% Aro	% NSO	% Asph	P/N	13Cs	13Ca
AU001	40.1	28.7	0.100	6.0	3.0	61.2	20.5	18.3	0.0		-27.29	-26.29
AU002	35.3	10.9	0.110	11.0	13.0	59.4	25.9	13.2	1.5		-25.97	-25.28
AU003	32.9	7.9	0.210	11.0	8.0	61.3	18.8	19.1	0.9		-22.32	-22.80
AU021	38.6	4.3	0.070	9.0	4.0	83.8	12.4	3.4	0.5	2.20	-24.66	-24.21
AU027	52.0	61.7	0.010	9.0	9.0	75.5	24.5	0.0	0.5		-26.93	-26.42
AU028	55.2	74.8	0.060	6.0	3.0	74.5	25.6	0.0	0.8		-27.04	-26.23
AU029	36.6	6.3	0.024	2.0	1.0	74.2	23.5	2.3	0.0	0.54	-28.28	-27.28
AU030	36.9	5.9	0.028	1.0	1.0	71.2	25.2	2.7	0.9	0.47	-28.41	-27.28
AU031	39.8	12.0	0.019	1.0	1.0	69.1	26.3	3.8	0.9	0.52	-28.35	-27.30
AU032	31.2	6.9	0.046	1.0	1.0	64.3	29.1	5.3	1.4	0.35	-28.02	-27.25
AU033	16.2	0.1	0.315	9.0	3.0	45.5	40.1	8.9	5.6	1.50	-27.97	-27.37
AU034	34.8	4.3	0.110	1.0	2.0	63.2	31.2	5.4	0.2	0.11	-28.02	-27.03
AU035	49.8	24.3	0.013	7.0	3.0	81.3	16.1	2.5	0.0	1.27	-27.99	-27.16
AU036	39.0	13.0	0.039	16.0	5.0	67.1	27.0	5.3	0.6	0.96	-27.67	-26.53
AU037	39.6	14.5	0.048	4.0	1.0	66.0	27.0	6.4	0.5	0.79	-27.69	-26.54
AU038	37.4	14.6	0.036	1.0	7.0	63.3	30.6	5.9	0.2	0.89	-27.67	-26.51
AU039	38.6	13.4	0.044	1.0	17.0	65.6	28.5	5.7	0.3	0.89	-27.68	-26.49
AU040	42.1	12.7	0.019	1.0	33.0	75.2	22.2	2.5	0.0	1.22	-27.23	-26.08
AU041	41.4	11.3	0.023	5.0	1.0	77.5	21.2	1.3	0.0	1.04	-27.25	-26.07
AU042	41.7	12.0	0.021	1.0	24.0	81.2	17.5	1.3	0.0	1.56	-27.17	-26.06
AU043	43.0	18.6	0.049	1.0	1.0	73.6	19.9	5.6	0.8	0.67	-25.40	-24.91
AU044	31.2	0.5	0.098	1.0	1.0	67.0	25.1	6.5	1.5	0.79	-25.98	-25.35
AU045	40.6	9.2	0.040	1.0	1.0	74.7	20.8	4.4	0.1	1.17	-27.43	-26.60
AU046	41.9	14.0	0.036	1.0	1.0	73.4	23.7	2.9	0.0	1.33	-27.44	-26.64
AU047	41.9	18.8	0.025	1.0	1.0	75.5	22.0	2.5	0.0	1.38	-27.42	-26.57
AU048	44.9	24.2	0.021	1.0	1.0	76.0	21.0	2.9	0.0	0.79	-27.42	-26.60
AU049	42.3	0.9	0.015	1.0	1.0	84.5	10.5	5.0	0.0	0.69	-27.81	-25.80
AU050	41.5	1.0	0.042	1.0	1.0	80.7	12.7	6.7	0.0	0.67	-27.70	-26.09
AU051	51.7	43.1	0.017	1.0	1.0	69.1	25.9	5.1	0.0	1.08	-27.40	-26.21
AU052	53.0	49.0	0.005	1.0	1.0	73.5	18.8	7.7	0.0	0.79	-27.32	-27.88
AU053	39.2	0.3	0.014	1.0	1.0	85.8	12.2	2.0	0.0	0.92	-27.92	-25.68
AU054	48.0	32.8	0.028	1.0	2.0	74.5	23.0	2.1	0.4	0.79	-26.18	-24.37
AU055	47.8	32.7	0.030	4.0	1.0	72.7	24.1	2.3	0.9	0.85	-26.22	-24.36
AU056	40.5	1.9	0.031	1.0	1.0	81.8	7.0	11.2	0.0	0.96	-26.78	-25.62
AU057		20.6	0.005	1.0	1.0	74.3	23.3	2.4	0.0	2.23	-25.77	-26.97
AU058	30.9	27.6	0.013	1.0	1.0	80.4	16.5	3.1	0.0	0.85	-26.87	-26.28
AU059	42.4	5.1	0.021	1.0	1.0	78.7	19.4	1.2	0.7	1.50	-26.71	-24.84
AU060	44.3	17.4	0.026	1.0	1.0	78.1	19.2	2.4	0.3	0.56	-26.56	-25.82
AU061	46.2	22.2	0.010	2.0	1.0	72.8	25.3	1.9	0.0	1.00	-27.17	-26.46
AU062	51.7	48.2	0.002	1.0	1.0	74.2	20.1	5.7	0.0	0.85	-26.65	-25.39
AU063	43.8	16.2	0.014	1.0	1.0	79.8	17.6	2.6	0.0	0.69	-26.81	-26.12
AU064	42.8	19.6	0.009	1.0	1.0	81.3	16.6	2.2	0.0	0.96	-26.84	-26.03
AU065	43.8	16.3	0.013	1.0	1.0	69.1	28.9	2.1	0.0	0.72	-26.69	-26.06
AU066	34.7	0.2	0.022	1.0	1.0	74.0	24.4	1.7	0.0	0.59	-26.45	-25.73
AU067	46.7	31.2	0.044	8.0	2.0	71.0	22.5	6.0	0.5	0.92	-25.97	-24.35
AU068	46.4	30.8	0.039	8.0	4.0	74.5	21.4	4.1	0.0	1.00	-26.14	-24.60
AU069	47.3	33.2	0.043	2.0	1.0	80.3	16.1	3.6	0.0	0.75	-26.13	-24.65
AU071	31.8	0.2	0.036	6.0	1.0	0.0	0.0	0.0	0.0	0.23	-26.60	-25.56
AU072	46.8	34.3	0.004	1.0	1.0	70.3	26.4	3.4	0.0	0.54	-25.25	-23.40
AU073		19.8	0.041	2.0	1.0	61.1	31.3	7.4	0.2	0.32	-26.70	-25.97
AU074	36.7	2.8	0.025	1.0	1.0	78.0	19.2	2.7	0.0	0.72	-26.72	-25.41
AU075	37.4	2.2	0.317	3.0	1.0	75.2	23.8	1.0	0.0	0.72	-26.75	-25.46
AU076	57.9	54.7	0.002	1.0	2.0	70.8	15.5	13.7	0.0	2.57	-26.49	-25.64
AU077	56.4	51.6	0.003	4.0	1.0	74.0	23.2	2.8	0.0	0.54	-26.58	-25.63
AU078	56.7	57.0	0.005	16.0	6.0	86.3	10.7	3.0	0.0	1.70	-27.12	-26.09
AU079	57.4	51.9	0.003	7.0	1.0	85.8	10.5	3.7	0.0	0.52	-26.46	-25.00
AU080	25.3	0.8	0.067	5.0	1.0	62.6	32.1	4.7	0.5	0.43	-26.93	-26.00
AU081	36.4	10.4	0.032	3.0	1.0	71.9	26.1	2.0	0.0	0.67	-26.81	-25.27
AU082	37.8	13.3	0.033	2.0	1.0	69.2	28.7	2.0	0.0	0.69	-26.73	-25.19
AU083	35.6	8.8	0.034	1.0	1.0	70.1	27.5	2.4	0.0	0.59	-26.85	-25.28
AU084	35.6	8.6	0.033	1.0	1.0	72.2	25.6	2.2	0.0	0.82	-26.79	-25.28
AU085	30.9	0.1	0.029	4.0	1.0	69.1	25.6	4.8	0.5	0.52	-27.12	-25.38
AU087	41.7	10.3	0.020	1.0	1.0	78.2	20.2	1.4	0.2	0.96	-27.05	-26.26

SampleID	API	<C15	% S	ppm Ni	ppm V	% Sat	% Aro	% NSO	% Asph	P/N	13Cs	13Ca
AU088		0.3	0.097	6.0	1.0	81.8	10.9	4.3	2.9	2.23	-24.65	-24.03
AU089		0.3	0.099	1.0	1.0	83.0	11.4	3.4	2.1	2.13	-24.68	-24.03
AU090	49.9	24.4	0.011	1.0	1.0	81.9	16.2	1.9	0.0	1.56	-27.24	-26.39
AU091	49.7	23.4	0.013	1.0	1.0	80.2	17.9	1.9	0.0	0.67	-27.25	-26.37
AU092	50.5	26.4	0.011	1.0	1.0	80.2	18.9	0.9	0.0	0.75	-27.29	-26.36
AU093	50.1	40.0	0.006	1.0	1.0	73.6	20.7	5.7	0.0	1.50	-26.80	-24.32
AU094	32.9	0.0	0.042	1.0	1.0	70.0	27.9	2.0	0.0		-26.93	-24.55
AU095	55.7	49.3	0.013	1.0	1.0	79.9	18.2	1.9	0.0	1.08	-26.90	-24.42
AU096	36.0	11.3	0.036	1.0	1.0	60.9	37.7	1.4	0.0	0.96	-25.63	-25.24
AU097	38.0	15.1	0.032	2.0	1.0	70.2	27.3	2.2	0.3	0.54	-27.27	-25.89
AU098	51.9	41.3	0.009	1.0	1.0	78.9	18.6	2.5	0.0	0.59	-26.98	-25.50
AU099	49.8	43.7	0.003	1.0	1.0	77.6	19.2	3.2	0.0	0.75	-27.06	-25.38
AU100	27.4	0.8	0.042	1.0	1.0	70.5	27.6	1.7	0.1	0.25	-26.45	-25.48
AU101	26.2	0.3	0.057	2.0	1.0	67.4	29.3	3.4	0.0	0.22	-26.90	-25.37
AU102	54.3	56.8	0.005	1.0	1.0	81.3	16.1	2.6	0.0	0.69	-27.26	-26.49
AU103	56.1	55.0	0.004	1.0	1.0	81.7	16.6	1.7	0.0	1.38	-27.42	-26.37
AU104	52.5	45.0	0.008	1.0	1.0	82.6	15.8	1.7	0.0	0.82	-27.34	-25.83
AU105	57.2	58.2	0.005	1.0	1.0	82.8	14.1	3.1	0.0	0.79	-27.14	-26.16
AU106	57.3	59.1	0.005	1.0	1.0	83.1	15.4	1.5	0.0	0.59	-27.17	-26.20
AU107	57.8	57.0	0.005	1.0	1.0	78.2	19.4	2.4	0.0	0.56	-26.97	-26.09
AU108	57.4	68.0	0.007	1.0	1.0	84.0	13.7	2.3	0.0	3.76	-27.26	-26.08
AU109	45.1	27.9	0.015	1.0	1.0	65.5	33.4	1.0	0.0	0.64	-25.73	-25.77
AU110	44.8	34.4	0.024	1.0	1.0	59.0	38.5	2.5	0.0	0.41	-26.96	-24.87
AU111	46.2	32.6	0.026	1.0	1.0	70.2	27.8	1.9	0.1	2.70	-27.08	-24.90
AU112	27.6	0.3	0.028	2.0	1.0	62.8	35.5	1.7	0.0	0.89	-25.68	-25.76
AU113	52.6	53.7	0.004	9.0	1.0	70.0	29.4	0.7	0.0	2.57	-27.22	-25.19
AU114	41.6	21.7	0.010	2.0	1.0	77.0	22.3	0.7	0.0	2.03	-27.38	-25.17
AU115	33.6	11.5	0.032	6.0	1.0	66.7	30.0	3.3	0.1	0.04	-27.11	-26.02
AU116	42.2	19.8	0.037	1.0	1.0	71.6	25.1	2.9	0.4	1.13	-26.57	-24.50
AU117	42.5	21.6	0.035	6.0	1.0	74.0	23.2	2.4	0.4	1.78	-26.64	-24.50
AU118	57.8	63.3				77.2	19.9	2.6	0.2	2.13	-26.45	-24.67
AU119	46.1	32.7	0.006	1.0	1.0	78.4	17.1	4.5	0.0	3.55	-26.81	-25.47
AU120	48.1	40.7	0.010	1.0	1.0	77.2	21.8	1.0	0.0	1.70	-23.76	-24.69
AU121	32.9	0.4	0.031	1.0	1.0	74.6	23.9	1.6	0.0	1.04	-23.82	-24.71
AU122	35.1	1.1	0.064	1.0	3.0	77.7	18.1	3.9	0.4	0.59	-32.48	-30.97
AU123	34.8	15.9	0.030			74.9	18.8	5.3	1.1	0.52	-32.31	-31.10
AU124	38.1	3.0	0.027	1.0	1.0	75.6	19.9	3.3	1.3	1.44	-24.52	-23.82
AU125	37.8	16.6	0.016	1.0	1.0	59.4	38.7	1.9	0.0	1.27	-25.53	-24.10
AU126	47.3	10.7	0.012	1.0	1.0	92.5	6.8	0.7	0.0	0.92	-31.77	-27.90
AU127	50.8	18.4	0.005	1.0	1.0	89.3	10.3	0.4	0.0	1.00	-32.48	-29.64
AU128	35.7	1.8	0.017	1.0	2.0	89.5	5.9	3.4	1.2	1.00	-32.52	-29.24
AU129		4.2	0.071	2.0	1.0	70.0	23.3	6.4	0.4	0.54	-32.68	-31.27
AU130	34.7	1.8	0.069	2.0	1.0	74.7	19.8	4.7	0.8	0.49	-32.38	-31.15
AU131	43.9	11.2	0.022	2.0	1.0	73.1	23.9	3.1	0.0	1.17	-27.91	-24.83
AU132	45.8	28.2	0.012	1.0	1.0	75.8	23.3	0.9	0.0	1.08	-27.93	-24.77
AU133	46.0	44.9	0.017	1.0	1.0	62.6	36.2	1.1	0.0	1.70	-26.10	-24.75
AU134	34.6	1.7	0.166	1.0	3.0	78.7	18.2	2.6	0.5	0.59	-30.58	-27.37
AU135	38.4	0.6	0.029	1.0	1.0	90.9	6.7	1.9	0.5	0.92	-32.57	-29.84
AU136	38.4	0.6	0.023	1.0	1.0	86.4	10.6	2.9	0.2	0.79	-32.39	-29.52
AU137	37.2	0.6	0.024	1.0	1.0	82.9	15.4	1.6	0.1	0.75	-32.57	-29.76
AU138	53.9	100.0	0.011	0.7	0.3	95.6	3.1	1.2	0.0	15.67	-31.44	-28.40
AU140	36.0	15.4	0.068	4.0	1.1	67.7	27.6	3.4	1.3	0.45	-29.21	-27.24
AU141	33.9	10.6	0.072	3.0	1.1	68.0	26.6	4.1	1.4	0.64	-29.18	-27.16
AU142	20.7	2.4	0.162	2.5	0.1	34.6	32.0	6.2	27.1	0.43	-31.48	-31.75
AU143	23.0	9.1	0.220	13.0	1.5	43.0	35.1	4.5	17.4	0.43	-29.23	-26.81
AU144		7.0	0.121	2.0	0.9	67.2	27.3	4.9	0.5	0.25	-27.05	-27.17
AU145	39.0	10.7	0.047	1.0	0.4	73.4	20.0	6.0	0.6	0.59	-27.31	-27.20
AU146		3.6	0.255	3.0	1.9	64.3	27.5	4.7	3.5	0.69	-30.21	-29.40
AU147	43.8	20.1	0.035	2.5	0.2	83.7	14.2	2.1	0.0	0.35	-31.10	-29.93
AU148		6.4	0.110	2.0	0.8	74.4	21.4	3.8	0.5	2.33	-28.81	-28.32
AU149		5.9	0.114	3.0	0.9	75.0	21.1	3.2	0.7	0.92	-28.82	-28.33
AU150		1.6	0.119	0.1	0.4	69.9	24.7	4.4	1.0	0.61	-27.91	-27.77
AU151		1.4	0.119	0.2	0.4	72.1	23.5	3.6	0.8	0.75	-27.86	-27.77

SampleID	API	<C15	% S	ppm Ni	ppm V	% Sat	% Aro	% NSO	% Asph	P/N	13Cs	13Ca
AU152	43.8	30.1				72.5	25.0	2.5	0.0	2.13	-26.47	-24.47
AU153	40.4	16.7				78.8	19.1	2.1	0.0	2.85	-26.50	-25.90
AU279	47.5		0.010	2.5	0.3						-26.96	-24.48
AU328	64.4	80.9	0.000	8.0	1.0	37.3	19.4	43.3	0.0		-26.57	-26.07
AU329		19.0				68.1	26.8	3.0	2.0	0.04	-29.26	-27.26
AU338		3.9				80.5	16.6	2.4	0.5	0.79	-27.46	-26.04
AU351	40.1	16.8	0.042	11.0	0.5	70.6	23.4	6.0	0.0	0.14	-28.38	-27.24
AU352	43.3	26.3	0.018	5.0	0.5	71.3	22.6	6.0	0.0	0.27	-28.34	-27.29
AU353	37.7	28.4	0.015	5.0	0.5	44.0	51.3	2.5	2.3	1.44	-24.57	-23.12
AU360	51.3	26.5	0.011	60.0	3.0	67.2	13.0	19.9	0.0	4.30	-27.13	-27.12
AU362	33.8	6.6	0.031	32.0	0.8	43.9	31.3	24.8	0.0	1.30	-26.68	-26.08
AU363	58.9	46.1	0.003	5.0	0.5	10.7	4.7	84.5	0.0	32.30	-26.62	-25.52
AU366	52.1	27.0	0.010	44.0	0.9	35.9	14.1	50.0	0.0	3.00	-27.22	-26.25
AU367	39.2	1.0	0.052	8.0	0.7	76.7	17.7	5.6	0.1	1.00	-32.66	-30.95
AU368	58.3	18.0	0.004	2.0	0.5	72.9	2.4	24.7	0.0	19.00	-31.49	-28.08
AU369	48.4	11.3	0.036	38.0	0.8	67.8	14.3	17.9	0.0	1.20	-29.94	-27.60
AU370	35.0	9.3	0.025	23.0	0.5	61.0	28.3	10.7	0.1	0.60	-26.81	-25.88
AU371	27.0	0.9	0.049	34.0	0.9	62.3	22.6	14.5	0.5	0.20	-26.77	-25.89
AU374	35.7	9.2	0.028	30.0	0.5	61.8	22.6	15.6	0.0	0.80	-26.58	-25.99
AU382	53.6	30.1	0.013	6.0	0.5	66.0	12.4	21.6	0.0	2.60	-27.15	-26.31
AU383	37.6	13.8				63.9	21.8	14.4	0.0	1.90	-26.43	-25.30
AU384	32.9	6.3				61.4	27.1	11.5	0.0	2.00	-26.53	-25.12
AU385	37.6	12.7				62.1	23.6	14.4	0.0	2.30	-26.62	-25.70
AU386	38.8	18.9				55.6	23.5	20.9	0.0	1.90	-26.25	-24.83
AU387	38.2	21.6				34.1	20.4	45.6	0.0	0.70	-27.39	-25.72
AU388	40.9	1.6				67.6	14.0	18.4	0.0	3.80	-27.28	-26.14
ID118	39.0	37.5	0.600	5.0	8.0	48.3	21.4	29.3	1.0		-22.28	-20.43
ID119		14.3	0.340			58.9	17.0	22.1	2.0		-22.57	-20.42
ID120	12.0	7.6	0.660	17.0	26.0	42.5	32.8	22.7	2.0		-22.94	-21.12
ID122	41.0	29.0		10.0	6.0	69.6	14.0	15.7	0.6		-30.01	-28.65
ID123	28.0	6.0	0.330	8.0	8.0	57.1	28.7	13.5	0.7		-29.92	-28.78
ID139	21.6	16.9	4.200	23.0	102.0	31.1	45.7	11.5	11.8		-29.02	-29.27
ID157	38.6	9.6	0.130	5.0	1.0	76.5	8.6	14.4	0.6		-25.71	-23.84
ID176	21.1	18.4	3.020			33.3	49.6	15.4	1.8		-29.12	-28.76
<C15 = % Light Ends; P/N = n-Paraffin/Naphthene (br/cyc); 13Cs & 13Ca = carbon isotope (permil) of C15+ sat and aro HC												

SampleID		nC15	nC16	nC17	Pr	nC18	Ph	nC19	nC20	nC21	nC22	nC23	nC24	nC25	nC26	nC27	nC28	nC29	nC30	nC31	nC32	nC33	nC34	nC35
AU001		9.70	9.24	8.35	4.35	7.75	1.91	7.37	7.08	6.69	6.35	5.81	4.95	4.92	4.15	3.55	1.84	1.54	1.23	0.92	0.61	0.31	0.00	-0.31
AU002		12.45	10.67	10.01	4.15	8.93	1.72	8.07	7.11	6.41	5.76	5.28	4.66	4.08	3.25	2.72	-0.89	-1.41	-1.92	-2.44	-2.96	-3.48	####	-4.51
AU003		15.82	12.90	11.48	4.63	9.33	1.99	7.45	6.42	5.55	4.70	4.21	3.46	3.05	2.42	2.02	-4.55	-5.32	-6.10	-6.88	-7.66	-8.44	####	-10.00
AU021		6.95	7.18	6.97	2.22	6.84	0.54	6.89	7.01	6.88	6.74	6.66	6.77	6.07	5.61	6.06	6.45	6.49	6.52	6.56	6.59	6.63	6.66	6.70
AU027		23.42	17.35	13.17	3.14	10.10	1.00	7.71	6.10	4.67	3.65	2.98	2.23	1.75	1.11	0.69	-10.21	-11.41	-12.61	-13.81	-15.01	####	####	-18.62
AU028		22.82	16.87	12.99	3.10	9.88	0.82	7.80	6.20	4.91	4.03	3.14	2.43	1.95	1.40	1.02	-9.37	-10.51	-11.66	-12.80	-13.94	####	####	-17.37
AU029		12.33	9.41	8.96	5.39	8.00	5.03	8.24	6.80	5.76	4.97	4.67	4.00	3.01	2.76	2.52	-1.69	-2.25	-2.81	-3.37	-3.93	-4.49	####	-5.60
AU030		15.61	11.94	10.28	7.00	8.66	5.89	8.18	6.30	5.01	4.23	3.62	2.92	2.25	1.86	1.63	-5.46	-6.31	-7.15	-7.99	-8.84	-9.68	####	-11.37
AU031		15.32	11.57	9.92	6.66	8.23	5.70	7.98	6.32	4.86	4.32	3.74	2.93	2.49	2.68	1.73	-4.70	-5.48	-6.27	-7.05	-7.84	-8.62	####	-10.20
AU032		15.51	9.06	8.23	7.91	7.92	6.96	7.48	6.43	4.52	4.44	4.25	3.51	3.06	2.49	2.05	-3.55	-4.25	-4.95	-5.65	-6.35	-7.05	####	-8.45
AU033	Biodegraded																							
AU034		12.20	10.06	9.78	6.13	8.77	4.48	9.15	7.29	5.74	5.34	4.61	3.83	2.93	2.31	1.90	-2.51	-3.14	-3.77	-4.39	-5.02	-5.65	####	-6.91
AU035		25.44	17.55	12.96	4.28	8.90	1.48	6.62	4.62	3.43	2.70	2.39	1.91	1.76	1.37	1.21	-11.18	-12.43	-13.69	-14.95	-16.21	####	####	-19.99
AU036		14.86	12.39	11.07	4.85	8.93	1.71	7.94	6.13	5.28	4.60	4.31	3.62	3.05	2.49	2.29	-3.93	-4.65	-5.38	-6.10	-6.83	-7.56	####	-9.01
AU037		14.85	12.23	11.06	4.98	9.04	1.68	8.10	6.31	5.38	4.66	4.46	3.82	3.24	2.67	2.61	-3.52	-4.23	-4.93	-5.64	-6.34	-7.05	####	-8.45
AU038		13.66	12.24	10.51	4.79	8.79	1.57	8.26	6.38	5.49	4.90	4.72	4.04	3.56	2.80	2.49	-2.77	-3.41	-4.06	-4.70	-5.35	-6.00	####	-7.29
AU039		13.23	11.20	10.61	4.70	8.73	1.69	8.48	6.44	5.64	4.94	4.83	4.11	3.64	2.90	2.62	-2.21	-2.82	-3.42	-4.03	-4.63	-5.24	####	-6.45
AU040		10.59	9.47	8.74	3.01	8.08	1.06	7.73	7.07	6.68	6.20	6.23	5.42	4.93	3.68	3.45	1.63	1.31	0.99	0.67	0.34	0.02	####	-0.63
AU041		10.48	9.36	8.63	2.98	7.93	1.12	7.82	7.12	6.78	6.29	6.37	5.52	5.04	3.77	3.61	1.95	1.65	1.34	1.04	0.74	0.43	0.13	-0.17
AU042		10.40	9.24	8.63	3.00	7.88	1.08	7.78	7.12	6.74	6.28	6.36	5.50	5.13	3.89	3.61								
AU043		11.32	9.06	8.38	3.39	7.40	1.12	7.20	6.43	6.01	5.87	6.02	5.40	5.06	4.25	3.85								
AU044		11.37	9.46	8.96	3.47	7.93	1.15	7.62	6.79	6.14	5.73	5.80	5.20	4.72	3.82	3.51								
AU045		10.34	9.60	8.71	2.78	7.70	1.04	7.41	6.84	6.34	5.92	5.95	5.41	5.03	4.08	3.90								
AU046		10.64	9.74	8.56	2.78	7.62	1.10	7.31	6.72	6.37	5.93	6.03	5.40	4.90	4.03	3.89								
AU047		10.53	8.94	8.54	2.79	7.85	1.06	7.58	6.88	6.50	6.05	6.03	5.42	5.06	4.08	3.86								
AU048		11.13	9.76	8.61	2.77	7.83	1.09	7.45	6.73	6.24	5.86	5.91	5.30	4.83	3.93	3.69								
AU049		29.13	21.00	14.79	6.02	9.69	1.36	6.60	4.02	2.41	1.57	1.12	0.73	0.51	0.30	0.30								
AU050		34.52	22.74	13.82	5.96	8.03	1.20	4.85	2.73	1.66	1.16	0.90	0.63	0.45	0.29	0.31								
AU051		21.84	16.07	12.13	5.24	9.10	1.57	7.69	6.00	4.78	3.99	3.39	2.44	1.95	1.32	1.07								
AU052		20.96	15.09	11.45	4.81	8.64	1.40	7.40	5.89	5.01	4.51	3.94	3.03	2.49	1.66	1.37								
AU053		15.35	15.48	14.68	4.68	12.71	1.51	10.77	8.15	6.05	4.19	2.88	1.69	0.90	0.47	0.24								
AU054		13.00	11.20	8.82	3.33	7.65	0.93	7.13	6.26	5.74	5.50	5.34	4.92	4.34	3.80	3.49								
AU055		12.70	10.99	9.06	3.20	7.57	0.98	7.08	6.07	5.73	5.44	6.45	4.77	4.39	3.56	3.36								
AU056		36.47	22.44	13.79	4.73	7.70	1.07	4.59	2.46	1.51	1.22	0.86	0.61	0.47	0.38	0.85								
AU057		39.90	14.63	6.85	1.66	3.63	0.32	2.41	2.69	1.55	4.76	5.26	4.91	4.03	2.83	2.23								
AU058		20.16	15.15	12.37	3.24	9.20	0.88	7.96	6.21	5.24	4.41	3.91	3.26	2.52	1.86	1.40								
AU059		10.02	8.91	8.05	1.74	7.55	0.50	7.16	6.58	6.52	6.00	6.12	5.69	5.34	4.51	4.30								
AU060		16.12	12.23	10.31	3.48	8.58	1.15	7.44	6.29	5.50	5.04	4.69	4.13	3.59	2.93	2.71								
AU061		18.47	14.15	11.71	3.32	9.37	1.00	7.95	6.45	5.22	4.59	4.09	3.33	2.73	2.06	1.78								
AU062		31.07	20.39	12.34	3.93	8.23	1.22	5.87	3.85	2.78	2.24	1.55	1.31	0.89	0.61	0.50								
AU063		18.96	14.69	11.51	3.64	9.18	1.04	7.63	6.05	4.96	4.21	3.90	3.30	2.70	2.16	1.87								
AU064		18.89	14.62	11.45	3.69	8.98	1.20	7.55	5.98	4.85	4.30	3.90	3.25	2.73	2.22	1.86								
AU065		18.70	14.41	11.51	3.67	9.45	1.01	7.61	6.19	4.95	4.38	3.91	3.25	2.70	2.12	1.83								
AU066		18.50	15.43	13.88	4.43	11.70	1.14	8.95	6.80	5.18	3.74	3.10	2.23	1.64	1.11	0.83								
AU067		11.81	10.44	8.63	3.77	7.54	1.22	7.26	6.32	5.74	5.53	5.53	4.96	4.47	3.69	3.52								
AU068		11.67	10.46	8.95	3.74	7.65	1.19	7.43	6.43	6.00	5.68	5.45	5.01	4.44	3.60	3.44								
AU069		12.87	10.52	9.05	3.96	7.53	1.23	7.26	6.40	5.81	5.46	5.33	4.63	4.27	3.36	3.32								
AU071		8.67	8.30	8.09	3.08	7.90	1.02	7.31	6.97	6.43	6.18	6.49	5.88	5.49	4.29	4.14								
AU072		19.56	15.85	12.02	1.76	9.62	0.65	7.83	6.25	5.12	4.58	3.74	3.01	2.47	1.92	1.56								
AU073		26.22	10.02	5.02	12.00	5.80	6.06	5.53	3.30	2.33	4.51	3.87	2.81	2.51	3.12	1.83								
AU074		10.34	8.45	7.81	3.02	7.43	1.13	7.07	6.75	6.34	6.39	6.59	6.07	5.50	4.35	4.09								
AU075		15.83	13.00	12.37	3.71	10.79	2.36	9.81	8.14	6.40	5.22	3.96	3.00	1.94	1.12	0.67								
AU076		25.48	16.86	13.19	4.28	9.57	1.15	7.47	5.61	4.17	3.21	2.55	1.78	1.24	0.75	0.55								
AU077		25.98	17.01	14.11	4.26	9.35	1.08	7.44	5.40	4.18	3.17	2.57	1.77	1.18	0.77	0.57								
AU078		35.84	17.05	11.97	5.82	8.63	2.01	5.97	3.64	2.16	2.29	2.25	0.69	0.43	0.00	0.00								
AU079		32.82	18.67	13.46	3.39	7.08	0.72	5.50	4.05	3.16	2.57	2.29	1.76	1.15	0.94	0.61								
AU080		30.88	6.95	3.53	2.69	3.80	0.47	2.72	5.53	3.00	4.48	3.55	2.12	1.68	2.79	0.72								
AU081		11.78	10.42	9.39	3.77	8.90	1.18	7.71	6.83	6.13	5.64	5.50	4.78	4.21	3.39	3.04								
AU082		11.99	9.60	9.45	3.29	9.04	1.17	7.93	6.95	6.20	5.87	5.55	4.88	4.20	3.41	3.22								
AU083		12.14	10.18	9.72	3.23	9.19	1.18	8.07	6.89	6.05	5.68	5.46	4.73	4.12	3.36	2.99								
AU084		10.58	10.02	9.69	3.27	9.20	1.25	8.16	7.10	6.43	5.82	5.62	4.87	4.28	3.47	3.08								
AU085		9.23	10.20	11.11	3.29	10.57	1.01	9.78	8.61	7.49	6.40	5.87	4.60	3.74	2.48	1.94								
AU087		18.26	13.51	11.40	3.66	9.21	1.22	7.71	6.24	5.13	4.43	4.09	3.41	2.90	2.27	2.03								
AU088		1.54	2.19	3.07	0.77	3.96	0.26	5.02	6.01	6.90	8.03	8.30	9.54	9.54	8.80	10.01								
AU089		2.29	3.04	3.72	0.93	4.65	0.40	5.40	6.50	7.10	7.85	8.34	9.05	8.64	8.11	9.24								
AU090		18.39	13.53	11.31	3.33	9.58	1.01	7.78	6.43	5.19	4.48	4.16	3.42	2.78	2.20	1.92								
AU091		18.07	13.09	11.14	3.25	9.44	1.06	7.60	6.20	5.21	4.31	4.04	3.48	2.76	2.16	2.49								
AU092		18.47	13.71	11.38	3.30	9.40	1.07	7.80	6.22	5.31	4.41	4.17	3.42	2.77	2.53	1.94								
AU093		17.54	15.59	12.31	4.07	10.16	1.17	8.42	6.36	5.29	4.31	3.74	3.14	2.41	1.67	1.55								
AU094		11.69	13.60	11.81	3.79	10.64	1.24	8.95	7.32	6.46	5.40	4.63	3.85	3.16	2.34	2.11								
AU095		16.79	16.19	11.80	4.28	9.99	1.20	8.06	6.34	5.39	4.58	3.82	3.10	2.48	1.74	1.49								
AU096		14.54	16.40	10.96	3.36	9.27	1.29	7.38	5.91	5.63	5.40	3.93	3.53	3.11	2.48	2.22								
AU097		16.86	11.83	10.84	6.01	9.20	2.10	8.04	6.33	5.24	4.51	4.03	3.34	2.90	2.21	2.01								
AU098		28.62	16.72	12.68	7.12	9.27	2.13	6.84	4.49	3.22	2.64	1.73	1.19	0.82	0.53	0.47								
AU099		29.31	17.30	12.82	6.99	8.89	2.17	6.72	4.86	3.02	2.21	1.80	1.23	0.81	0.52	0.47								
AU100		41.21	10.56	7.00	3.31	6.22	4.04	4.35	3.11	3.39	3.26	2.83	2.25	1.84	1.51	1.38								
AU101		11.37	10.26	9.98	2.41	8.75	1.40	7.73	6.57	5.89	5.49	5.28	4.80	4.36	3.85	3.59								
AU102		31.01	16.20	11.41	7.58	7.60	2.01	5.48	3.10	1.95	3.85	1.20	0.75	0.56	0.27	0.00								
AU103		32.09	17.38	12.48	8.46	8.30	2.38	5.90	3.66	2.28	1.92	1.32	0.93	0.52	1.28	0.00								
AU104		23.07	16.33	13.26	5.89	9.20	1.47	7.40	5.19	4.04	3.63	2.78	2.13	1.48	1.18	0.92								
AU105		30.34	17.22	12.97	7.49	8.72	1.92	5.98	3.53	2.33	1.66	1.34	0.79	0.55	0.71	1.19								
AU106		30.37	17.23	12.64	7.19	11.21	1.95	5.95	3.61	2.41	1.62	1.33	0.83	0.44	0.30	0.37								
AU107		31.77	17.03	12.12	8.53	8.33	1.90	5.92	3.77	2.46	1.84	1.61	1.15	0.98	0.62	1.02								
AU108		28.29	13.21	9.53	8.39	7.33	2.39	5.75	4.08	3.34	2.64	2.64	2.26	1.93	1.54	1.31								
AU109		13.57	15.17	10.02	2.07	8.32	1.39	7.08	6.04	5.82	4.83	4.34	3.86	3.33	2.91	4.23								
AU110		13.78	11.16	8.81	2.61	7.44	1.04	7.04	6.13	5.76	5.44	5.24	4.88	4.50	3.88	3.96								
AU111		13.90	11.44	9.41	2.80	8.00	1.07	7.66	6.79	6.43	5.94	5.55	4.74	4.05	3.48	2.85								
AU112		10.32	13.76	10.48	2.45	8.79	1.07	7.51	6.50	6.28	5.52	4.83	4.10	3.78	3.18	2.80								
AU113		22.49	16.52	12.68	4.23	9.75	1.08	7.67	5.86	4.47	3.56	2.93	2.26	1.75	1.38	0.97								
AU114		21.66	16.59	12.80	3.82	10.32	1.29	8.06	6.19	4.77	3.70	3.03	2.24	1.69	1.19	0.92								
AU115		16.53	11.09	10.20	3.76	9.61	2.04	8.17	6.83	5.95	5.71	4.81	3.80	3.13	2.37	1.93								
AU116		10.88	9.31	8.27	2.60	7.64	0.92	6.89	6.23	6.02	5.64	5.64	5.30	4.98	4.18	4.44								

SampleID		nC15	nC16	nC17	Pr	nC18	Ph	nC19	nC20	nC21	nC22	nC23	nC24	nC25	nC26	nC27	nC28	nC29	nC30	nC31	nC32	nC33	nC34	nC35
AU117		10.02	9.55	8.36	2.73	7.83	0.86	7.01	6.34	6.02	5.86	5.75	5.32	5.08	4.14	4.41								
AU118		13.77	10.85	9.18	3.09	7.94	0.92	7.11	6.13	5.57	4.91	4.86	4.42	3.97	3.40	3.58								
AU119		18.87	14.79	12.32	4.69	9.91	1.33	8.44	6.61	5.35	4.25	3.71	2.76	2.18	1.38	1.30								
AU120		12.39	9.91	8.57	3.17	7.34	0.95	7.35	6.84	6.28	5.85	6.07	5.32	4.73	3.88	3.49								
AU121		8.67	9.02	8.96	3.18	8.60	1.07	8.16	7.81	7.27	6.93	7.11	6.57	5.93	4.85	4.49								
AU122		9.32	7.81	7.57	2.33	6.83	1.78	6.73	6.11	5.51	5.42	5.95	5.38	5.26	5.07	5.11								
AU123		5.24	5.43	6.54	3.61	6.43	3.23	6.92	5.99	5.22	5.20	6.24	5.58	5.60	5.40	5.55								
AU124		5.08	5.32	5.75	1.02	6.30	0.36	6.66	6.96	7.11	7.43	7.83	7.93	7.74	6.26	7.08								
AU125		11.89	11.93	10.57	2.60	9.43	0.99	8.24	6.83	6.11	5.20	4.99	4.31	3.64	3.15	2.62								
AU126		17.63	13.83	12.59	2.67	10.91	1.85	9.66	7.85	6.16	4.74	3.93	2.60	1.79	1.42	0.97								
AU127		22.07	16.14	13.74	3.62	10.91	2.09	8.97	6.77	5.06	3.82	3.14	2.06	1.39	0.16	0.07								
AU128		2.75	2.82	3.22	0.72	3.65	0.61	4.10	4.40	4.79	5.24	6.56	6.72	7.33	8.31	8.73								
AU129		10.91	8.14	7.51	3.30	6.39	2.31	6.32	5.46	4.98	4.84	5.48	4.91	4.89	4.93	4.88								
AU130		6.54	5.90	6.76	4.00	6.50	3.49	6.90	5.86	4.99	4.99	5.94	5.43	5.29	5.26	5.25								
AU131		0.84	2.63	5.14	1.01	7.91	0.57	10.18	10.96	11.69	10.45	9.92	7.91	6.46	4.40	3.69								
AU132		11.38	10.85	10.16	1.37	9.45	0.46	8.69	7.45	7.14	5.98	5.62	4.59	3.99	3.14	2.79								
AU133		12.92	13.85	11.39	5.08	10.83	1.53	9.84	8.54	7.11	5.90	4.98	3.48	3.03	0.93	0.59								
AU134		8.33	7.87	7.91	4.21	7.30	1.70	7.19	6.24	5.89	5.21	5.25	4.62	4.40	4.26	4.39								
AU135		4.75	4.98	6.03	1.35	6.75	1.18	7.59	7.58	7.53	7.30	7.87	6.96	6.44	5.98	5.48								
AU136		4.94	5.19	6.42	1.44	7.06	1.37	7.98	8.01	7.67	7.68	7.97	6.89	6.13	5.52	4.90								
AU137		4.76	5.04	6.04	1.36	6.79	1.19	7.62	7.64	7.40	7.34	7.79	6.87	6.41	5.97	5.42								
AU138		52.79	22.43	9.86	3.33	3.82	1.12	1.71	0.91	0.78	0.64	0.65	0.48	0.39	0.33	0.22								
AU140		16.31	10.69	10.41	4.88	7.63	8.59	6.97	4.81	4.29	3.59	3.55	3.04	2.27	2.53	2.59								
AU141		15.55	10.56	9.99	4.82	7.15	8.36	6.72	4.77	4.25	3.54	3.71	2.97	2.67	2.38	2.26								
AU142		19.59	19.08	21.58	0.96	5.79	1.55	12.52	3.13	2.44	2.14	1.81	2.76	1.44	1.39	0.96								
AU143		16.40	10.84	10.92	4.43	7.40	9.48	6.48	4.38	3.80	3.18	3.25	2.67	2.34	2.11	2.05								
AU144		11.94	9.09	8.36	4.61	7.58	2.89	7.62	6.48	5.89	5.47	5.23	4.77	4.43	3.56	3.21								
AU145		12.81	10.39	9.28	5.92	8.17	4.24	8.14	6.60	5.53	4.89	4.58	3.95	3.06	2.72	2.42								
AU146		7.78	9.13	7.88	3.63	6.23	3.06	6.12	5.09	5.06	5.14	5.11	5.31	5.05	4.47	4.41								
AU147		12.39	10.52	10.19	4.44	8.58	2.25	8.34	6.54	5.90	4.93	4.75	4.10	3.29	2.71	2.76								
AU148		12.14	9.33	8.32	4.50	7.43	3.19	7.50	6.36	5.70	5.21	4.89	4.51	4.02	3.17	3.09								
AU149		12.30	9.45	8.64	4.62	7.70	3.20	7.58	6.55	5.68	5.30	4.93	4.44	3.99	3.06	2.84								
AU150		6.97	6.70	7.60	6.05	7.77	4.12	7.96	7.00	6.23	5.87	5.57	5.18	4.98	3.82	3.60								
AU151		6.59	6.40	7.82	5.82	7.47	3.98	7.80	6.67	6.14	5.79	5.38	5.14	4.79	3.82	3.75								
AU152		9.42	10.23	8.58	3.32	8.21	0.93	7.11	6.26	5.89	5.67	5.63	5.25	4.95	4.26	4.44								
AU153		16.29	13.78	11.62	3.82	9.30	1.30	7.83	6.28	5.16	4.42	4.18	3.53	3.03	2.42	2.14								
AU279		11.25	10.44	9.07	1.96	8.75	0.66	7.54	6.73	6.23	5.76	5.73	5.18	4.66	3.95	3.68								
AU328		19.30	14.43	12.12	4.22	10.15	1.09	7.11	5.85	4.52	4.25	2.56	1.73	1.44	0.88	1.65								
AU329		16.28	10.75	10.35	4.91	7.53	8.49	6.77	4.73	4.23	3.51	3.65	2.99	2.60	2.70	1.96								
AU338		7.82	7.07	6.91	3.08	6.54	0.84	6.42	6.05	6.00	6.11	6.35	6.06	6.12	5.22	5.31								
AU351		17.00	12.59	10.80	6.71	8.51	5.73	8.63	6.45	4.82	4.01	3.73	2.90	2.25	1.74	1.44								
AU352		15.37	11.32	9.81	5.63	8.18	5.02	8.74	6.92	5.63	4.79	4.41	3.73	3.12	2.30	1.92								
AU353		21.81	19.05	12.26	1.80	9.55	0.84	7.49	5.57	5.26	4.02	2.89	2.06	1.59	1.03	0.86								
AU360		20.09	15.72	12.75	3.55	9.79	1.18	7.68	5.92	4.78	3.89	3.39	2.73	2.26	1.64	1.43								
AU362	Biodegrade	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00								
AU363		36.08	22.15	13.38	4.17	8.02	1.26	4.69	2.77	1.69	1.10	0.83	0.54	0.34	0.24	1.27								
AU366		17.64	14.80	12.19	3.70	9.51	1.35	7.95	6.29	5.15	4.20	3.71	3.08	2.44	1.89	1.61								
AU367		9.72	8.46	8.03	2.44	7.12	1.98	7.23	6.35	5.76	5.58	6.01	5.36	5.09	4.79	4.65								
AU368		53.43	22.93	10.00	3.36	3.77	1.16	1.86	0.76	0.46	0.33	0.32	0.19	0.20	0.13	0.13								
AU369		16.51	14.33	12.60	3.34	9.41	2.99	7.93	6.19	4.68	3.75	3.47	2.82	2.48	2.19	1.94								
AU370	Biodegraded																							
AU371	Biodegraded																							
AU374	Biodegraded																							
AU382		17.47	14.30	11.92	3.46	9.82	1.27	7.92	6.40	5.28	4.32	3.98	3.21	3.20	2.01	1.73								
AU383		10.84	10.10	9.57	3.12	8.59	1.18	8.07	6.97	6.38	5.72	5.59	4.93	4.39	3.44	3.15								
AU384		8.46	8.47	8.70	3.07	8.44	1.25	8.41	7.39	6.97	6.30	6.35	5.63	4.84	3.82	3.54								
AU385		11.02	10.23	9.82	3.55	9.09	1.32	8.16	7.14	6.29	5.57	5.39	4.64	4.07	3.21	3.07								
AU386		9.23	8.79	8.63	2.87	8.26	1.15	7.74	7.07	6.65	6.09	6.22	5.53	5.00	3.87	3.71								
AU387		11.13	9.88	9.10	3.62	8.53	1.53	7.34	6.24	5.99	5.33	5.83	4.96	4.90	3.87	3.36								
AU388		7.13	7.61	6.90	3.10	6.56	0.81	6.51	6.13	6.11	6.09	6.38	6.21	6.19	5.03	5.53								
ID118		20.90	14.00	11.28	11.05	7.84	4.58	7.61	5.71	3.35	2.12	1.72	1.87	1.79	1.31	1.09								
ID119		16.08	13.54	11.03	7.20	8.60	3.30	7.01	5.77	4.75	3.79	3.09	2.47	2.21	1.98	1.53								
ID120	Biodegraded																							
ID122		17.77	14.74	12.42	4.00	9.82	1.74	8.60	6.84	5.70	4.60	3.60	2.56	2.13	1.50	1.07								
ID123	Biodegraded																							
ID139		15.50	13.55	10.94	1.81	9.34	1.96	8.20	6.95	5.76	4.53	4.06	3.27	2.74	2.43	1.93								
ID157		13.78	14.07	13.83	6.52	12.11	1.88	10.46	8.56	6.88	4.89	3.39	2.17	1.47	0.00	0.00								
ID176	Biodegraded																							

APPENDIX B

Biomarker ID and Concentration Data

Sterane and Terpane Peak Identifications

Peak	Formula	MW	Sterane ID*
S1	C27H48	372	13β, 17α diacholestane (20S)
S2	C27H48	372	13β, 17α diacholestane (20R)
S3	C27H48	372	5α cholestane (20S) +
		372	5β cholestane (20R)
S4	C27H48	372	5α, 14β, 17β cholestane (20R) +
	C29H52	400	13β, 17α diastigmastane (20S)
S5+S5B**	C27H48	372	5α, 14β, 17β cholestane (20S)
S6	C27H48	372	5α cholestane (20R)
S7	C29H52	400	diastigmastane
S8	C28H50	386	5α ergostane (20S)
S9	C28H50	386	5α, 14β, 17β ergostane (20R) +
		386	5β ergostane (20R)
S10+S10B	C28H50	386	5α, 14β, 17β ergostane (20S)
S11	C28H50	386	5α ergostane (20R)
S12	C29H52	400	5α stigmastane (20S)
S13	C29H52	400	5α, 14β, 17β stigmastane (20R)
S14+S14B	C29H52	400	5α, 14β, 17β stigmastane (20S) +
		400	5β stigmastane (20R)
S15	C29H52	400	5α stigmastane (20R)

*assumes 8β,9α,14α,17α unless otherwise stated. dia=rearranged

**based on the 217 and 218 m/z mass chromatograms, respectively

Peak	Formula	MW	Terpane ID
C19	C19H34	262	tricyclic diterpane
C20	C20H36	276	tricyclic diterpane
C21	C21H38	290	tricyclic diterpane
C22	C22H40	304	tricyclic terpane
C23	C23H42	318	tricyclic terpane
C24	C24H44	332	tricyclic terpane
C25	C25H46	346	tricyclic terpane
TET	C24H42	330	teteracyclic terpane
C26	C26H48	360	tricyclic terpane
C28	C28H52	388	extended tricyclic terpane
C29	C29H54	402	extended tricyclic terpane
C30	C30H56	416	extended tricyclic terpane
Ts	C27H46	370	18α, 21β -22,29,30-trisnorhopane
C27T	C27H46	370	17α,18α,21β -25,28,30-trisnorhopane
Tm	C27H46	370	17α, 21β -22,29,30-trisnorhopane
C28H	C28H48	384	17α, 18α, 21β -28,30-bisnorhopane
C29H	C29H50	398	17α, 21β -30-norhopane
C29D	C29H50	398	18α -30-norneohopane
C30X	C30H52	412	17α, 15α -methyl-27-norhopane (diahopane)
C29M	C29H50	398	17β, 21α -30-normortane
OL	C30H52	412	oleanane
C30H	C30H52	412	17α, 21β hopane
C30M	C30H52	412	17β, 21α moretane
C31H	C31H54	426	17α, 21β -30-homohopane (22S+22R)
GA	C30H52	412	gammacerane
C32H	C32H56	440	17α, 21β -bishomohopane (22S+22R)
C33H	C33H58	454	17α, 21β -trishomohopane (22S+22R)
C34H	C34H60	468	17α, 21β extended hopane (22S+22R)
C35H	C35H62	482	17α, 21β extended hopane (22S+22R)

Biomarker ppm Data
(relative to branched/cyclic HC fraction)

SampleID	C19T	C20T	C21T	C22T	C23T	C24T	C25S	C25R	TET	C26S	C26R	Ts	C27T	Tm	C28DM	C28H	C29DM	C29H	C29D	C30X	OL	C30H	C30M	C31S	C31R	GA	C32S	C32R	C33S	C33R
AU001	9.8	8.4	7.9	4.3	9.2	4.9	1.5	1.7	19.1	2.2	2.3	56.6	1.8	20.5	1.6	5.8	1.7	50.5	47.3	53.9	1.1	141.4	11.7	54.4	41.4	9.8	48.0	26.9	21.3	14.0
AU002	11.3	10.8	10.5	4.6	12.7	7.8	2.6	2.3	33.4	3.4	3.4	91.2	11.3	47.7	2.9	5.3	1.6	127.7	85.6	68.1	9.3	289.8	38.3	102.7	80.4	10.4	70.1	51.6	47.6	32.4
AU003	3.4	3.9	4.2	1.9	6.2	4.0	1.6	1.6	11.2	1.5	1.7	29.1	3.8	26.9	6.7	3.7	0.4	65.4	29.4	18.0	5.9	107.8	17.1	32.7	27.6	0.6	19.0	15.9	10.3	8.3
AU021	20.0	12.1	2.3	1.1	3.6	2.3	0.9	0.9	31.4	1.0	0.9	16.1	1.3	41.2	1.6	2.5	0.4	88.6	16.5	27.6	2.1	144.7	17.2	64.2	44.9	2.9	49.9	33.3	24.1	16.4
AU027	8.0	4.0	3.7	1.4	4.5	2.6	0.4	0.3	4.7	1.3	1.1	12.6	0.4	8.7	4.6	1.6	2.8	24.3	9.1	6.2	1.9	45.2	7.1	14.9	10.4	0.3	9.4	6.2	4.9	3.7
AU028	6.5	3.7	4.8	1.8	4.8	3.3	0.7	0.3	5.9	1.2	1.2	13.7	0.4	9.2	4.6	0.5	3.3	22.0	9.4	6.6	1.0	40.6	7.0	14.1	10.6	1.9	8.9	6.6	5.0	4.0
AU029	0.3	1.1	2.9	1.0	6.1	4.7	2.3	2.4	0.7	3.0	3.0	3.4	0.3	0.4	0.3	0.7	0.2	2.2	2.4	2.7	0.3	4.3	0.3	1.9	1.7	2.5	1.4	0.3	1.1	0.9
AU030	1.8	3.4	9.8	3.1	21.6	17.1	7.5	8.0	2.8	9.8	9.7	9.8	18.6	5.1	16.9	5.0	17.2	10.1	7.4	8.8	1.7	22.6	3.2	7.8	6.6	5.9	6.4	4.6	5.0	3.5
AU031	1.5	3.5	10.4	3.4	22.0	18.4	7.9	8.0	3.1	10.0	10.3	10.6	18.6	5.2	16.0	4.7	16.7	13.1	7.9	8.9	1.1	26.2	3.2	10.0	7.7	6.4	7.4	5.5	6.1	3.9
AU032	3.3	7.7	22.9	8.2	59.3	50.0	23.2	23.6	6.1	27.2	26.3	14.4	68.1	9.7	67.8	9.2	67.9	16.6	12.9	14.6	5.9	33.4	4.0	12.4	10.1	10.5	10.1	7.3	8.1	5.8
AU033	8.1	20.9	63.6	18.4	154.1	128.2	64.9	68.3	19.0	69.1	68.1	45.9	168.0	29.0	170.0	32.4	160.1	50.6	17.3	36.1	15.0	104.8	13.4	39.7	30.0	37.0	34.1	25.6	30.7	18.9
AU034	2.2	2.9	5.4	2.6	14.9	11.3	6.4	6.1	3.7	7.3	6.8	8.9	1.8	2.9	0.4	2.7	0.4	8.3	5.8	5.7	1.5	19.1	1.8	6.9	6.0	6.3	5.5	4.4	4.2	2.7
AU035	2.4	1.9	2.1	0.8	2.7	1.3	0.5	0.4	5.0	0.6	0.6	14.3	0.5	8.8	0.5	1.9	0.3	26.1	15.8	8.0	0.8	56.2	7.5	20.7	16.0	1.7	13.6	10.6	8.9	6.2
AU036	10.3	7.5	6.8	3.5	8.4	4.7	1.3	1.2	22.9	2.1	1.8	72.9	2.7	33.2	1.7	5.3	1.4	88.4	70.6	48.6	2.1	221.9	31.4	81.4	63.9	16.8	58.6	42.9	38.5	28.1
AU037	12.3	9.2	8.2	3.9	9.9	5.4	1.9	1.2	27.2	2.3	2.3	84.5	3.2	39.6	1.8	6.4	1.5	105.2	84.5	57.2	2.3	256.9	36.8	99.6	76.0	9.6	69.8	52.1	45.4	32.5
AU038	10.8	8.4	7.6	3.7	9.0	5.7	1.9	1.6	25.6	2.1	2.2	85.8	3.6	39.5	1.9	5.7	2.3	113.2	77.3	55.4	2.5	279.9	36.7	99.9	73.8	9.5	66.6	49.4	45.9	30.4
AU039	11.5	9.1	7.8	4.0	9.8	6.0	1.9	1.4	27.4	2.4	2.2	86.0	3.5	41.2	0.9	6.7	1.8	108.8	87.0	59.4	2.7	269.5	38.0	102.6	80.5	21.2	72.5	52.4	46.9	33.2
AU040	7.1	4.6	4.1	2.3	4.8	2.8	0.9	0.8	10.5	1.2	1.1	32.4	0.7	11.3	0.3	3.5	0.7	28.0	28.2	31.8	0.4	77.9	10.0	31.0	22.5	6.5	22.1	15.7	13.2	9.1
AU041	5.3	3.7	2.9	1.6	3.2	1.7	1.0	0.7	6.8	1.0	0.7	24.0	1.4	8.6	0.9	2.4	0.7	21.7	22.4	24.3	0.5	62.7	7.5	25.5	19.9	5.7	19.2	13.1	11.0	7.8
AU042	6.2	4.2	3.6	2.0	4.2	2.7	0.8	0.7	9.7	1.0	1.1	30.3	1.5	10.1	0.4	3.2	0.8	26.1	25.7	26.9	1.9	70.0	8.3	28.2	20.4	2.7	20.3	14.3	12.2	8.6
AU043	5.1	3.9	3.5	1.7	5.0	3.3	1.3	1.1	13.4	1.6	1.3	43.0	1.7	23.5	1.4	3.2	0.7	70.0	43.7	27.3	1.3	162.5	21.9	55.9	44.3	5.0	38.3	28.2	27.0	19.5
AU044	10.0	7.8	7.3	3.4	10.8	6.6	2.2	2.0	26.6	3.1	3.1	74.9	3.0	39.0	1.2	5.6	2.0	104.4	69.3	54.3	2.6	212.9	31.5	90.8	67.5	10.2	65.2	46.5	43.2	30.6
AU045	4.4	3.4	3.8	2.0	5.7	1.4	0.8	0.8	9.6	1.1	1.1	25.9	0.6	15.1	0.7	2.3	1.2	38.7	22.8	16.7	1.0	78.6	11.4	32.1	23.5	2.4	21.7	15.0	13.4	9.5
AU046	5.7	4.3	4.9	2.5	6.2	3.3	1.3	1.0	11.9	1.6	1.2	30.3	0.9	18.5	1.1	2.9	0.8	46.5	28.1	21.5	0.9	96.2	14.7	39.3	29.2	3.2	26.4	18.8	15.5	11.1
AU047	3.9	3.0	3.3	1.6	4.0	2.3	0.7	0.7	7.7	1.0	0.9	20.9	1.3	12.2	0.7	1.9	0.5	32.0	18.8	14.3	1.0	66.5	9.6	26.6	19.5	1.8	16.8	11.9	10.1	7.2
AU048	2.9	2.2	2.4	1.2	3.3	1.7	0.5	0.6	5.9	0.7	0.7	16.2	0.5	9.6	0.4	1.5	0.4	24.6	15.3	11.1	0.3	49.0	7.6	21.6	15.4	1.8	14.4	9.5	7.9	5.9
AU049	1.4	1.0	0.9	0.4	1.4	0.7	0.3	0.3	1.1	0.3	0.3	1.7	0.1	1.5	0.3	0.1	0.2	5.0	1.2	0.1	0.2	4.6	0.5	2.2	1.6	0.4	1.4	1.0	1.0	0.7
AU050	0.9	0.6	0.8	0.5	2.6	1.2	0.7	0.7	4.0	0.7	0.7	8.8	0.4	6.4	0.3	0.3	0.4	21.7	5.9	0.4	0.3	15.2	1.1	7.2	5.0	0.6	3.7	2.5	2.6	1.7
AU051	2.4	2.0	1.9	1.0	3.5	1.6	0.7	0.5	2.9	0.6	0.6	5.5	0.2	3.1	0.1	0.4	0.3	8.5	3.6	1.4	0.1	10.5	1.1	4.1	2.8	0.3	2.0	1.5	1.4	1.0
AU052	1.9	1.4	1.5	0.7	4.6	3.1	2.6	2.4	5.0	2.5	2.5	24.6	2.5	18.2	1.1	2.9	4.8	75.5	25.5	8.0	13.3	125.6	19.4	39.8	27.8	6.2	23.2	15.8	12.5	9.1
AU053	0.6	0.4	0.2	0.1	0.3	0.2	0.1	0.4	1.1	0.2	0.3	1.6	1.3	2.2	0.2	0.0	0.2	12.2	1.8	0.4	0.1	12.8	1.1	9.2	7.1	1.3	6.0	4.3	4.6	3.0
AU054	2.6	1.8	1.7	0.9	2.1	1.4	0.5	0.5	4.7	0.7	0.6	16.6	1.9	5.6	0.8	2.1	0.6	16.0	14.9	14.7	1.4	42.0	4.9	17.4	12.2	1.6	13.0	9.1	7.9	5.7
AU055	4.1	2.8	2.3	1.5	3.4	2.0	0.6	0.7	7.0	1.0	0.9	25.4	3.1	8.5	1.4	1.0	0.5	24.0	23.3	23.3	1.7	63.1	7.3	26.0	19.1	2.3	18.3	12.9	10.8	8.2
AU056	1.8	1.5	1.7	0.7	3.5	2.2	1.1	1.0	1.4	1.1	1.0	2.7	2.0	2.8	0.5	0.7	0.8	6.4	2.3	1.1	0.6	11.4	1.8	3.4	3.9	0.4	1.9	1.7	1.3	1.1
AU057	0.0	0.0	0.0	0.0	0.2	0.1	0.0	0.0	0.1	0.1	0.0	0.4	0.9	0.3	0.1	0.1	0.1	0.4	0.8	0.1	0.1	1.0	0.1	0.5	0.4	0.2	0.2	0.2	0.3	0.3
AU058	2.3	1.6	1.3	0.6	1.5	1.1	0.3	0.3	2.0	0.5	0.4	4.9	2.4	3.6	1.3	0.9	1.4	8.4	3.7	2.3	0.3	15.7	3.1	5.2	4.0	0.4	3.2	2.4	1.9	1.5
AU059	5.0	2.5	1.1	0.6	1.2	0.7	0.4	0.1	5.4	0.4	0.1	7.2	2.8	8.9	0.6	2.7	0.2	18.8	6.2	17.2	1.1	30.8	5.1	13.3	13.5	1.0	9.9	6.5	4.9	3.4
AU060	8.0	6.2	6.3	2.4	8.8	6.0	1.9	1.6	21.0	3.0	2.6	54.2	3.7	39.4	25.0	15.0	19.8	128.8	54.2	19.6	3.2	233.0	37.4	72.2	53.8	5.6	44.8	32.3	24.4	18.9
AU061	2.7	2.0	2.3	1.2	3.1	1.8	0.6	0.6	3.2	0.9	1.0	8.9	0.6	4.4	4.0	1.5	4.2	11.6	7.6	4.9	0.6	24.2	3.7	8.4	6.2	0.2	5.8	3.9	3.5	2.7
AU062	1.6	1.0	0.8	0.3	0.7	0.3	0.1	0.1	0.5	0.1	0.1	0.6	3.5	0.3	0.2	0.1	0.1	0.9	0.4	0.2	0.1	1.3	0.1	0.6	0.5	0.1	0.4	0.3	0.2	0.1
AU063	4.3	2.8	3.1	1.6	4.3	2.6	0.4	0.8	5.4	1.3	1.2	14.3	5.2	7.6	16.5	2.8	10.9	19.9	12.4	7.5	1.1	41.9	6.3	13.5	9.3	1.3	8.9	6.0	5.3	0.6
AU064	4.0	2.5	3.1	1.5	4.4	3.1	1.0	1.0	5.8	2.0	1.5	15.9	5.5	8.1	16.4	3.1	11.6	21.5	13.3	8.3	1.3	42.4	6.2	13.7	9.8	1.6	9.2	7.0	5.0	4.0
AU065	3.5	2.5	2.9	1.3	3.7	2.7	0.8	0.8	5.5	1.4	1.2	14.6	5.7	7.8	15.8	2.9	11.4	19.7	12.4	8.0	1.3	40.7	5.6	13.0	9.6	1.5	8.8	6.4	5.5	3.6
AU066	5.0	2.7	2.6	1.2	2.7	1.7	0.5	0.5	2.6	0.6	0.5	4.6	0.4	1.6	1.0	0.7	0.6	3.9	2.3	2.1	0.3	7.8	1.1	2.4	1.7	0.3	1.3	1.1	0.8	0.5
AU067	7.2	4.6	5.1	2.8	6.7	4.1	1.2	1.2	14.3	1.7	1.6	52.7	1.9	16.2	3.6	5.5	2.1	45.3	45.8	39.3	3.6	121.4	13.5	49.1	34.5	4.4	36.5	25.9	21.3	15.4
AU068	8.0	4.3	4.5	2.3	5.6	3.3	1.1	1.1	12.2	1.6	1.4	42.5	3.5	12.6	2.8	4.6	2.0	34.8	36.1	32.0	1.1	96.7	11.5	39.4	30.0	3.7	29.8	21.0	18.3	12.8
AU069	6.0	4.2	4.5	2.5	5.9	3.2	1.2	1.2	12.0	1.5	1.6	41.0	1.4	12.3	2.9	4.7	1.9	34.3	36.5	32.4	3.0	97.4	11.4	38.3	29.4	3.7	29.2	20.2	17.3	12.0
AU071	7.5	5.5	6.4	3.5	8.8	5.9	2.0	2.1	17.0	3.5	3.4	48.9	4.6	15.7	3.4	9.7	2.3	59.4	43.3	23.5	4.9	137.2	17.2	45.0	33.6	4.6	28.9	19.3	16.7	11.2
AU072	1.2	1.3	0.4	0.3	0.6	0.4	0.2	0.2	0.1	0.2	0.0	0.8	3.6	0.1	0.1	0.1	0.1	0.4	0.4	0.1	0.1	0.5	0.2	0.1	0.2	0.2	0.2	0.2	0.2	0.2

Biomarker ppm Data
(relative to branched/cyclic HC fraction)

SampleID	C19T	C20T	C21T	C22T	C23T	C24T	C25S	C25R	TET	C26S	C26R	Ts	C27T	Tm	C28DM	C28H	C29DM	C29H	C29D	C30X	OL	C30H	C30M	C31S	C31R	GA	C32S	C32R	C33S	C33R
AU073	9.1	7.1	7.3	3.3	9.3	5.9	1.9	1.5	15.6	2.9	2.6	44.4	2.6	21.6	29.9	7.9	20.5	58.8	33.7	18.3	2.5	124.0	16.8	40.3	31.0	3.8	26.1	19.2	14.6	10.1
AU074	7.0	5.4	5.9	3.2	8.3	5.5	2.0	2.0	15.6	3.0	2.7	50.8	4.9	15.9	3.4	8.5	2.7	57.7	39.2	21.2	1.8	125.4	15.6	43.4	32.7	4.2	28.4	20.3	17.3	11.2
AU075	7.8	7.5	6.5	4.8	17.3	6.9	2.4	2.4	12.6	1.8	2.0	5.9	0.4	2.3	0.3	0.2	0.1	5.1	2.5	0.2	0.5	4.3	0.4	1.8	1.3	0.2	0.9	0.7	0.6	0.5
AU076	1.6	0.9	0.8	0.4	0.9	0.5	0.1	0.1	0.6	0.1	0.1	0.6	2.6	0.5	0.2	0.3	0.1	1.0	0.4	0.1	0.1	1.6	0.2	0.7	0.6	0.3	0.4	0.3	0.3	0.4
AU077	1.9	1.0	1.0	0.5	1.2	0.6	0.1	0.1	0.7	0.2	0.1	0.8	3.1	0.7	0.2	0.3	0.3	1.2	0.4	0.3	0.3	2.0	0.1	0.9	0.7	0.3	0.7	0.5	0.4	0.3
AU078	5.8	4.8	2.8	1.1	2.6	1.7	0.5	0.5	3.2	0.6	0.6	6.5	0.7	3.5	12.2	2.4	9.1	7.6	4.6	3.3	0.7	14.8	2.3	4.2	3.2	0.8	2.6	2.3	1.6	1.1
AU079	0.8	0.6	0.5	0.2	0.7	0.3	0.1	0.2	0.6	0.1	0.1	0.9	3.8	0.7	0.1	0.1	0.1	2.1	0.7	0.4	0.3	3.4	0.5	1.3	0.9	0.2	0.6	0.5	0.6	0.4
AU080	9.6	8.0	9.3	4.6	12.1	8.6	2.9	2.7	20.0	4.2	3.8	55.3	3.8	28.6	48.1	12.1	33.6	76.3	46.6	26.0	3.5	157.4	22.9	57.1	41.6	5.2	37.9	27.2	22.4	14.4
AU081	6.5	4.6	5.2	2.7	6.6	4.2	1.2	1.3	9.8	2.0	1.8	30.1	6.8	9.0	8.9	4.5	5.5	25.6	23.2	15.9	0.8	58.9	7.3	20.9	15.6	2.2	15.1	10.7	8.7	6.1
AU082	6.2	4.3	5.6	2.7	7.1	4.5	1.3	1.3	10.1	1.8	1.8	31.8	7.3	9.4	8.3	4.4	5.2	26.4	22.8	16.1	1.0	64.6	7.8	23.5	16.9	2.4	16.7	11.9	9.5	6.9
AU083	5.9	5.4	6.2	3.0	7.7	4.5	1.7	1.6	11.2	2.1	2.1	31.0	8.2	9.3	8.8	4.7	5.7	27.0	24.8	17.2	2.2	67.0	8.0	22.9	17.2	2.4	16.8	11.3	9.7	6.7
AU084	5.8	5.2	6.2	2.9	7.4	4.6	1.5	1.5	11.5	2.1	2.0	32.1	1.7	9.5	8.9	4.8	6.0	27.3	25.4	18.3	2.0	68.4	8.2	23.8	17.6	2.4	16.5	11.4	9.6	6.7
AU085	4.7	3.8	3.2	1.4	4.0	2.6	1.1	0.4	6.2	1.6	1.4	15.8	3.6	11.6	5.4	2.8	3.8	27.3	11.7	7.1	1.0	48.7	9.4	16.7	13.1	1.3	11.0	7.6	6.6	4.7
AU087	2.0	2.3	2.6	1.6	5.8	3.5	1.6	1.3	8.4	1.6	1.3	14.6	2.0	23.9	11.1	1.8	6.4	47.5	10.9	4.8	2.1	60.9	6.2	21.6	15.8	6.1	11.5	8.0	6.1	4.0
AU088	16.9	10.7	1.8	0.9	2.3	1.4	0.5	0.5	26.7	0.6	0.8	10.4	1.6	29.0	0.5	1.3	1.4	55.3	9.7	17.4	0.5	74.5	9.4	31.0	25.4	6.0	27.7	16.9	12.3	10.1
AU089	13.3	8.1	1.5	0.1	1.7	0.9	0.3	0.3	17.9	0.7	0.6	7.3	0.8	19.7	0.3	1.2	0.9	37.5	6.2	11.6	0.9	49.8	6.5	20.5	16.6	1.5	19.5	11.4	8.0	6.6
AU090	2.2	1.7	1.6	0.9	2.0	1.3	0.5	0.4	2.0	0.6	0.6	4.7	1.7	2.5	2.6	0.9	2.1	6.5	4.0	2.6	0.2	14.8	2.2	5.2	3.6	0.6	3.3	2.4	2.2	1.5
AU091	0.7	0.5	0.6	0.4	0.6	0.5	0.2	0.2	0.8	0.2	0.3	2.0	0.7	1.1	1.1	0.4	0.9	2.4	1.5	0.9	0.2	4.7	0.6	1.4	1.1	0.4	0.9	0.7	0.1	0.2
AU092	1.6	1.3	1.2	0.6	1.5	1.0	0.2	0.3	1.6	0.4	0.1	4.1	1.3	2.2	2.5	0.7	1.9	5.2	3.1	2.4	0.3	11.7	1.7	4.1	3.1	0.4	2.6	1.8	1.6	1.0
AU093	1.6	0.7	0.6	0.3	0.7	0.4	0.1	0.1	0.9	0.2	0.2	1.1	0.4	0.4	0.2	0.1	0.1	0.6	0.5	0.6	0.1	1.0	0.2	0.4	0.2	0.2	0.2	0.2	0.1	0.3
AU094	6.5	3.4	2.3	1.2	2.1	1.2	0.3	0.3	3.6	0.5	0.4	5.2	0.6	3.6	0.4	0.9	0.2	7.7	3.9	4.4	0.3	14.5	1.8	5.0	3.3	0.9	2.8	1.8	1.1	0.8
AU095	4.0	2.5	1.6	0.2	1.4	0.7	0.2	0.2	1.8	0.3	0.3	2.2	1.5	0.9	0.2	0.2	0.1	1.6	1.3	1.8	0.0	3.7	0.5	1.4	1.1	0.1	1.3	0.8	0.7	0.6
AU096	1.5	0.9	0.3	0.2	1.6	1.0	0.3	0.7	1.7	0.4	0.4	2.9	0.9	5.0	1.1	0.2	0.2	11.4	2.3	1.6	0.6	16.8	1.8	7.4	5.8	3.1	4.7	4.0	3.8	2.7
AU097	2.9	2.5	1.8	0.7	2.1	1.6	0.4	0.4	3.1	0.5	0.6	7.2	1.5	3.9	13.7	2.0	10.0	8.6	5.6	4.9	0.9	20.8	3.4	7.2	5.9	0.9	5.3	4.1	3.1	2.2
AU098	3.4	2.6	1.5	0.6	1.5	1.0	0.3	0.3	1.8	0.4	0.3	3.5	1.4	1.8	6.6	0.8	4.1	3.8	2.2	1.7	0.3	6.8	0.9	1.9	1.4	0.1	1.1	0.7	0.5	0.1
AU099	2.5	2.0	1.1	0.5	1.4	0.9	0.2	0.1	1.6	0.3	0.3	2.8	1.0	1.4	5.4	0.6	3.0	2.5	1.6	1.2	0.2	4.5	0.7	1.1	0.8	0.1	0.4	0.4	0.1	0.1
AU100	11.0	7.3	2.9	1.6	3.5	2.5	0.6	0.8	9.5	1.1	0.8	14.9	3.7	9.3	2.8	3.0	1.7	12.4	7.7	6.4	0.7	19.0	2.4	4.0	3.4	0.3	1.9	1.5	1.2	0.6
AU101	20.6	11.7	5.6	1.9	4.1	2.6	0.1	0.5	9.8	0.9	0.7	14.1	0.8	10.7	0.6	3.7	0.3	22.3	9.3	8.9	0.4	43.3	6.7	13.2	9.9	0.8	8.1	5.5	3.9	2.9
AU102	4.7	3.8	2.2	1.1	2.8	2.1	0.7	0.6	5.3	1.0	0.8	9.5	3.9	5.3	14.7	2.4	9.6	12.4	6.7	5.0	0.7	21.8	2.9	5.8	4.8	0.9	3.0	2.6	1.2	1.1
AU103	4.0	3.4	2.0	0.9	2.1	1.5	0.5	0.5	3.9	0.6	0.6	8.6	3.4	4.3	13.6	2.3	9.1	10.3	6.9	5.2	0.9	21.3	3.1	5.8	4.9	1.5	3.2	2.6	1.5	1.1
AU104	8.0	6.9	4.1	2.2	5.6	3.7	0.9	1.2	10.0	1.2	1.4	14.3	3.4	11.6	16.4	2.2	8.9	19.1	8.2	5.8	0.9	27.1	3.1	7.0	4.9	1.5	3.4	2.4	2.0	0.5
AU105	4.6	3.6	2.5	1.2	3.0	2.0	0.3	0.5	4.7	0.6	0.8	8.7	3.7	4.7	13.2	2.0	8.1	8.8	5.4	4.2	0.6	16.6	2.3	3.8	3.1	0.7	1.8	1.4	1.0	0.5
AU106	4.5	4.4	2.8	1.2	3.8	2.3	0.6	0.6	4.5	0.9	0.7	7.9	2.9	3.8	10.0	1.5	6.0	6.7	4.3	2.8	0.6	10.6	1.8	2.0	1.8	0.0	1.2	0.3	0.6	0.7
AU107	5.0	4.7	2.8	1.5	4.2	2.9	0.9	0.7	6.7	1.2	0.3	11.4	4.4	5.9	17.7	2.4	10.7	11.6	7.3	4.9	0.3	19.7	2.6	4.3	3.3	0.4	1.8	1.7	1.3	0.4
AU108	4.4	3.8	2.8	1.1	2.7	2.0	0.7	0.5	3.9	0.7	0.6	5.5	2.4	4.1	6.6	3.3	3.6	6.5	3.0	2.2	0.3	9.4	1.6	2.2	1.6	0.3	0.9	0.8	0.7	0.4
AU109	0.6	0.5	0.2	0.4	0.4	0.2	0.3	0.3	0.7	0.2	0.2	2.2	0.6	0.2	0.2	0.1	0.2	0.8	1.1	1.7	0.3	1.9	0.4	0.9	0.9	0.5	0.9	0.6	0.3	0.5
AU110	1.4	1.0	0.7	0.5	0.8	0.5	0.2	0.2	1.9	0.3	0.2	3.9	0.4	1.7	0.2	0.3	0.3	3.4	2.5	4.1	0.2	6.6	1.0	2.5	1.6	0.3	1.4	1.1	0.2	0.4
AU111	1.7	1.1	0.6	0.5	0.8	0.5	0.1	0.1	2.0	0.3	0.3	4.9	0.5	2.3	0.3	0.9	0.2	4.4	3.4	5.5	0.2	9.2	1.1	3.7	2.7	0.4	2.6	1.9	1.1	0.9
AU112	0.8	1.4	1.1	0.9	1.1	0.9	0.6	0.9	0.6	0.6	1.1	3.6	0.6	1.1	1.1	0.8	0.8	1.1	1.5	2.5	0.8	2.2	1.2	0.8	0.8	0.6	0.9	0.8	1.4	1.5
AU113	3.7	2.4	1.5	0.7	1.5	1.1	0.4	0.4	2.1	0.4	0.4	1.7	0.6	2.3	0.3	0.3	0.5	3.5	1.1	0.5	0.3	3.8	0.9	0.7	1.1	0.8	0.7	0.6	0.8	0.4
AU114	7.0	4.2	1.8	1.2	2.2	1.5	0.5	0.1	4.8	0.6	0.5	8.2	2.7	7.1	0.1	4.7	0.3	16.0	5.8	4.5	0.3	25.8	3.6	6.3	4.9	0.5	3.2	2.1	1.3	1.0
AU115	9.8	9.4	5.0	2.5	8.0	6.2	1.9	1.4	16.8	3.3	2.4	48.8	18.7	25.5	75.5	13.5	53.6	54.5	35.9	24.4	4.1	107.8	16.1	32.2	23.1	1.3	18.5	12.8	8.7	5.6
AU116	7.2	4.5	3.0	1.8	4.2	2.6	0.4	0.7	8.4	1.0	1.2	19.4	1.5	10.8	1.5	3.1	1.1	27.3	16.5	17.8	2.1	68.6	9.0	25.9	19.9	2.5	22.4	15.1	13.4	9.6
AU117	2.0	1.4	0.9	0.6	1.3	0.8	0.1	0.3	3.1	0.4	0.4	8.9	0.6	4.5	0.7	1.4	0.3	11.4	6.9	7.2	0.7	27.2	3.2	9.6	6.6	2.0	6.5	4.4	3.0	2.3
AU118	2.2	1.6	1.1	0.7	1.5	1.1	0.3	0.2	3.7	0.4	0.4	10.0	1.2	5.4	0.7	1.5	0.2	12.4	7.6	7.2	0.4	28.2	3.5	10.4	7.2	0.2	6.1	4.2	2.8	2.1
AU119	2.9	2.3	1.6	0.9	2.2	1.4	0.2	0.5	3.1	0.7	0.2	5.9	1.4	3.0	4.0	1.0	2.4	7.3	4.1	2.1	0.3	13.3	1.6	3.9	2.8	0.4	2.0	1.4	1.0	0.2
AU120	1.9	1.9	1.0	0.7	1.4	0.8	0.2	0.5	1.4	0.3	0.4	2.7	1.2	1.8	1.5	1.1	1.3	4.7	1.9	2.4	0.3	9.7	1.5	3.7	2.8	1.0	2.6	2.1	1.6	0.3
AU121	1.7	1.2	1.2	0.3	1.5	0.5	0.2	0.2	1.8	0.4	0.2	3.8	1.1	2.4	1.7	1.5	0.8	4.4	2.2	2.4	0.5	6.5	0.6	2.2	1.8	0.3	0.8	0.4	0.9	0.2
AU122	3.4	9.5	21.9	10.5	54.2	34.0	18.0	18.1	4.5	18.5	16.5	18.7	1.5	7.5	1.5	3.0	0.9	25.6	14.2	12.9	1.1	57.6	7.3	18.3	14.8	11.0	13.8	9.0	7.7	6.9

Biomarker ppm Data
(relative to branched/cyclic HC fraction)

SampleID	C19T	C20T	C21T	C22T	C23T	C24T	C25S	C25R	TET	C26S	C26R	Ts	C27T	Tm	C28DM	C28H	C29DM	C29H	C29D	C30X	OL	C30H	C30M	C31S	C31R	GA	C32S	C32R	C33S	C33R	C34S
AU123	0.5	1.8	3.4	1.1	9.5	5.8	3.8	3.9	1.7	3.9	3.7	4.6	0.2	3.1	0.1	0.6	0.2	9.2	3.5	2.2	0.3	19.7	2.2	6.2	4.3	3.4	3.9	2.8	2.9	2.1	2.1
AU124	4.6	3.2	0.6	0.5	1.0	0.3	0.2	0.3	4.7	0.4	0.4	4.2	1.2	11.4	0.2	0.4	0.4	24.9	4.8	6.0	1.1	37.9	7.6	13.4	11.7	1.1	9.9	6.8	4.9	4.5	3.6
AU125	2.0	1.2	0.3	0.3	1.0	0.2	0.2	0.2	1.0	0.2	0.2	1.4	0.9	1.6	0.2	0.2	0.2	4.0	1.4	2.1	0.2	6.7	0.9	2.5	1.7	0.4	1.6	1.3	1.1	0.8	0.6
AU126	0.3	0.2	0.6	0.3	1.1	1.0	0.4	0.4	0.2	0.5	0.5	0.2	0.3	0.4	0.2	0.2	0.1	0.2	0.1	0.3	0.1	0.3	0.2	0.2	0.3	0.3	0.3	0.4	0.3	0.7	0.7
AU127	0.6	0.9	2.1	1.0	4.2	3.5	1.4	1.6	0.3	1.6	1.5	0.8	0.9	0.3	0.1	0.1	0.1	0.6	0.6	0.5	0.3	0.7	0.2	0.4	0.2	0.2	0.3	0.4	0.3	0.3	0.3
AU128	2.0	2.7	3.1	0.9	5.6	0.7	1.3	1.3	0.3	2.3	1.9	1.6	0.7	0.8	0.8	0.9	0.4	0.7	0.7	1.3	0.4	1.1	0.5	0.8	0.5	1.2	0.7	0.5	1.1	0.7	0.8
AU129	3.0	7.9	18.7	7.7	43.4	27.2	15.6	15.2	4.6	14.7	13.0	15.1	1.5	8.0	0.5	0.7	0.4	20.0	13.1	10.0	1.7	48.4	5.8	16.1	12.9	9.6	11.7	7.8	6.7	5.6	5.2
AU130	2.3	8.7	19.7	7.9	50.0	28.2	18.1	18.0	6.3	16.1	15.4	16.9	1.7	11.5	0.8	2.1	0.8	34.6	12.6	7.6	2.5	69.3	8.7	22.9	16.6	9.7	14.9	9.4	9.8	7.6	6.8
AU131	18.1	12.1	10.7	4.2	19.0	13.1	6.3	6.8	11.3	7.0	6.8	13.0	1.7	12.1	1.4	2.2	0.5	35.3	8.0	13.6	2.0	64.0	7.9	20.3	16.4	7.1	17.5	10.5	9.1	7.7	7.3
AU132	0.7	0.6	0.4	0.2	0.5	0.3	0.1	0.1	0.8	0.1	0.1	1.1	0.3	0.6	0.1	0.3	0.1	1.2	0.8	2.0	0.1	2.3	0.5	0.7	0.8	0.1	0.6	0.4	0.1	0.3	0.2
AU133	1.3	1.1	0.7	0.5	1.6	0.8	0.2	0.3	3.1	0.4	0.4	6.1	2.2	4.6	0.2	0.3	0.1	15.7	4.6	2.5	0.4	18.0	1.5	8.5	5.5	0.6	4.6	3.0	2.3	1.5	1.0
AU134	9.8	10.2	10.8	5.0	21.9	14.6	6.4	7.1	3.5	8.6	7.5	6.4	1.1	1.8	0.4	0.0	0.5	2.6	2.3	4.3	1.3	2.6	0.6	6.0	1.7	4.5	1.0	0.0	0.3	1.0	1.0
AU135	0.7	3.4	4.7	1.8	9.5	7.0	3.1	3.5	0.2	4.1	3.5	3.6	0.6	1.4	0.6	0.3	0.4	2.6	2.5	4.0	0.3	6.5	0.4	2.6	2.2	2.5	2.1	1.6	0.4	1.5	0.2
AU136	1.2	2.9	4.9	1.7	9.4	6.7	3.3	3.4	0.9	4.2	3.5	3.6	0.7	1.0	0.2	0.5	0.2	2.6	3.0	4.6	0.3	7.3	0.4	2.7	2.4	2.9	2.9	1.5	1.1	1.6	1.7
AU137	1.0	3.6	5.0	2.2	10.9	8.0	3.8	4.2	1.1	4.7	4.6	4.0	0.4	1.3	0.5	0.8	0.4	3.1	3.4	4.9	0.4	8.4	0.4	4.0	3.1	3.1	3.2	2.0	3.8	1.7	2.3
AU138	0.8	1.3	2.9	1.0	6.7	5.0	2.4	2.2	1.3	2.0	2.0	2.8	0.5	2.9	0.4	0.8	0.4	9.0	2.1	1.0	0.8	12.7	1.5	5.4	3.8	1.1	2.9	2.4	2.3	1.3	0.6
AU140	5.0	8.7	14.9	4.9	25.2	18.6	9.0	6.2	15.5	12.3	13.2	39.9	7.2	34.4	17.6	13.6	12.2	76.4	31.4	15.9	1.0	220.0	27.8	68.1	47.6	47.5	35.9	24.7	21.5	15.1	13.5
AU141	4.6	7.1	11.9	4.3	17.3	13.5	6.9	4.4	11.6	9.0	9.6	31.0	5.9	25.7	13.6	9.5	9.9	58.0	22.5	11.7	1.0	159.2	18.4	49.1	34.6	35.5	26.9	16.9	15.3	10.1	10.1
AU142	14.3	19.3	39.0	12.6	97.8	73.2	28.5	29.4	36.4	41.6	38.2	38.2	4.9	62.1	0.9	3.3	1.4	120.5	27.7	16.4	2.0	193.6	21.9	83.2	61.1	20.1	53.9	36.6	30.0	20.2	19.5
AU143	5.9	9.0	18.2	7.5	43.9	31.9	16.7	13.5	22.0	21.3	22.6	67.9	9.0	60.0	10.1	9.0	14.3	120.5	63.0	28.4	1.0	286.8	39.7	96.0	70.8	82.1	55.1	36.2	33.5	22.3	22.1
AU144	19.0	16.7	32.7	14.2	57.0	42.6	14.2	13.7	22.7	15.8	15.9	55.2	1.7	15.1	1.7	3.8	0.9	33.1	31.3	29.6	1.1	86.0	7.4	28.3	22.6	7.7	27.0	17.1	14.1	9.9	11.5
AU145	7.6	5.9	10.2	4.7	21.4	17.2	5.8	6.1	5.6	8.1	8.3	16.5	0.8	7.2	1.1	1.0	0.6	13.8	9.0	9.8	0.5	25.9	3.4	7.8	6.6	3.0	5.0	3.1	2.9	2.2	2.0
AU146	115.7	75.8	48.5	15.8	80.4	72.0	27.0	25.5	356.3	23.7	18.4	303.9	3.7	254.0	5.2	14.7	3.2	423.0	203.1	103.5	5.0	719.5	72.4	299.0	227.7	20.0	268.3	181.3	161.1	120.0	218.6
AU147	0.6	0.5	0.4	0.3	0.8	0.2	0.0	0.3	0.9	0.1	0.4	1.2	0.2	2.0	0.1	0.4	0.1	2.3	0.4	0.8	0.0	3.7	0.5	1.7	1.4	0.3	1.4	0.8	0.3	0.5	0.6
AU148	11.2	15.2	27.0	9.7	49.6	40.4	14.1	13.5	17.9	15.0	13.8	34.1	0.9	10.7	1.8	2.3	0.8	25.2	21.6	19.2	1.0	56.5	5.2	18.7	14.8	5.0	16.2	9.7	8.6	6.6	7.1
AU149	9.3	11.0	20.0	7.5	39.5	30.3	11.6	12.0	14.2	11.7	10.8	28.9	0.8	9.1	1.4	2.1	0.7	21.6	18.9	16.7	0.9	48.3	4.3	16.5	12.1	4.3	13.9	8.6	7.9	5.7	6.2
AU150	10.2	10.9	22.8	9.1	42.7	32.7	11.4	11.3	18.6	13.0	11.7	49.0	0.6	15.4	1.5	4.4	0.9	39.2	33.4	27.9	2.7	111.5	9.7	39.1	28.1	9.4	33.7	22.2	17.1	14.1	14.2
AU151	16.8	18.8	37.9	15.6	69.1	52.0	17.5	18.4	29.5	20.4	18.1	70.8	1.2	21.7	2.9	6.5	1.2	57.4	46.4	42.6	1.0	151.7	14.0	53.3	39.3	12.3	46.7	29.8	22.8	17.2	17.9
AU152	2.6	2.1	1.9	1.2	4.8	2.6	1.0	0.9	3.8	0.9	0.9	9.1	0.7	4.1	0.8	1.0	0.3	10.9	6.6	6.7	0.1	22.1	2.6	9.0	6.2	0.4	6.1	4.5	3.3	2.3	2.2
AU153	12.2	9.2	8.4	3.4	12.8	7.7	2.4	2.1	17.7	3.1	3.0	37.9	9.9	23.3	22.6	7.4	19.0	65.3	33.5	15.2	2.3	128.1	19.5	44.3	32.8	3.8	30.2	21.0	19.0	12.6	12.3
AU279	2.0	1.5	1.0	0.4	1.2	0.7	0.2	0.2	1.4	0.5	0.2	3.2	1.4	2.3	0.2	0.3	0.3	7.3	3.4	2.4	0.4	15.3	1.8	5.7	4.2	0.3	4.7	2.8	2.7	2.0	1.6
AU328	2.0	3.0	4.0	2.0	9.0	5.0	2.0	2.0	5.0	2.0	1.0	10.0	1.0	7.0	2.0	1.0	0.1	17.0	8.0	4.0	0.1	31.0	4.0	8.0	6.0	1.0	4.0	3.0	2.0	1.0	1.0
AU329	1.0	2.0	3.0	1.0	6.0	5.0	2.0	2.0	4.0	3.0	4.0	16.0	3.0	13.0	7.0	6.0	4.0	32.0	12.0	6.0	2.0	88.0	10.0	27.0	18.0	19.0	15.0	10.0	8.0	6.0	6.0
AU338	15.7	10.5	5.4	2.5	6.4	5.6	1.4	1.4	31.0	2.3	1.7	101.4	1.6	81.0	1.4	8.6	1.8	198.1	102.7	63.0	2.1	429.0	73.2	130.1	103.0	9.9	83.1	62.8	43.1	34.1	25.7
AU351	2.0	2.9	6.8	2.0	13.5	10.1	5.3	4.8	2.2	5.9	6.3	5.6	8.7	2.4	9.5	1.0	9.3	6.0	5.1	5.1	0.3	13.7	0.8	8.4	3.4	1.7	5.0	3.4	3.7	2.3	2.9
AU352	0.9	1.6	3.4	0.9	5.7	4.4	2.0	2.1	0.9	2.6	2.5	2.2	1.4	0.6	0.2	0.4	0.4	2.0	1.8	1.7	0.0	3.7	0.6	3.2	1.4	0.5	0.9	0.3	1.0	0.7	0.6
AU353	1.2	0.7	0.5	0.2	0.4	0.3	0.1	0.1	0.4	0.1	0.1	0.4	0.7	0.2	0.1	0.1	0.0	0.3	0.3	0.6	0.1	0.7	0.1	0.5	0.3	0.1	0.2	0.2	0.2	0.2	0.2
AU360	19.8	14.3	13.5	4.8	16.7	4.0	4.0	3.2	16.7	7.1	9.5	16.7	4.8	15.9	7.1	10.3	8.7	31.0	19.8	11.1	12.7	32.5	11.9	20.6	10.3	23.8	34.1	13.5	27.0	27.0	28.6
AU362	22.3	15.3	15.5	2.3	15.5	7.4	2.1	2.1	16.3	2.9	2.9	25.8	7.4	11.1	8.1	2.7	6.4	22.3	16.1	6.8	35.5	35.3	5.8	12.4	10.3	2.3	5.6	8.1	6.6	8.1	5.8
AU363	0.5	0.2	1.0	0.4	0.3	0.1	0.2	0.4	0.3	0.5	0.3	2.1	9.0	1.5	0.5	0.7	0.4	3.5	1.5	1.1	0.5	5.9	0.9	2.1	1.8	0.6	1.6	1.7	2.1	1.4	1.2
AU366	8.8	5.4	4.0	6.1	6.1	6.1	4.7	3.4	8.8	2.0	4.0	14.8	6.7	8.1	8.8	8.8	9.4	9.4	9.4	8.1	8.1	14.8	7.4	12.1	13.5	12.1	12.8	6.1	12.1	18.9	18.2
AU367	0.5	1.2	4.4	1.5	13.0	10.9	5.9	5.9	2.1	7.2	7.7	10.7	1.4	4.2	0.7	0.7	1.2	14.2	9.7	6.9	0.1	39.4	4.0	20.5	9.7	7.6	9.8	8.0	7.0	6.3	6.5
AU368	0.7	0.5	0.7	0.7	0.7	0.7	0.7	1.4	0.5	2.1	1.8	3.7	13.4	4.2	1.4	2.1	2.5	9.9	3.2	2.3	4.6	12.3	3.7	5.1	3.5	4.9	3.0	3.5	5.3	4.6	7.9
AU369	2.0	3.0	4.0	2.0	9.0	6.0	3.5	3.5	3.0	3.1	3.1	5.7	2.7	2.1	0.8	1.6	0.8	5.6	4.3	4.2	0.0	8.8	1.3	6.3	3.0	1.5	3.3	0.7	1.9	2.3	1.5
AU370	6.1	6.3	5.4	2.3	6.7	4.5	2.0	2.0	12.6	2.8	2.8	38.0	11.9	18.2	34.4	6.8	25.0	56.7	37.4	19.4	1.0	132.7	16.9	46.3	33.1	5.1	31.6	21.9	19.8	13.1	12.3
AU371	7.2	6.8	5.4	2.1	8.7	5.6	1.8	1.2	16.1	2.7	2.8	53.2	17.7	29.5	49.3	11.9	40.8	94.0	53.9	28.9	1.0	202.5	28.6	72.0	49.9	17.6	49.1	33.7	28.6	20.6	20.3
AU374	6.1	4.2	4.0	1.5	5.0	3.5	1.4	1.4	8.5	1.5	1.5	24.7	9.6	10.0	10.7	4.4	8.0	30.6	20.0	11.4	1.0	71.5	8.8	23.6	16.6	1.7	16.1	11.8	9.2	6.2	5.8
AU382	1.6	1.0	1.0	1.3	1.3	1.3	1.6	0.6	1.9	1.0	1.0	5.1	1.9	3.2	2.9	3.8	1.6	8.3	5.1	3.2	4.8	6.1	6.7	3.8	5.4	2.6	0.0	6.1	8.0	8.3	10.8
AU383	6.0	5.2	4.9	1.1	6.0	3.3	1.1	1.1	7.9	1.3	1.0	21.5	3.3	5.7	3.4	2.2	1.9	16.7	13.9	9.4	0.1	38.8	5.5	13.6	8.7	2.3	7.5	6.5	5.0	2.0	2.3

Biomarker ppm Data
(relative to branched/cyclic HC fraction)

SampleID	C19T	C20T	C21T	C22T	C23T	C24T	C25S	C25R	TET	C26S	C26R	Ts	C27T	Tm	C28DM	C28H	C29DM	C29H	C29D	C30X	OL	C30H	C30M	C31S	C31R	GA	C32S	C32R	C33S	C33R	C34S
AU384	9.0	8.0	6.3	2.0	9.0	4.3	1.5	1.5	11.9	2.3	1.8	36.1	1.8	9.6	12.0	5.5	8.4	27.7	25.6	19.5	0.1	67.4	7.4	23.3	16.4	2.5	15.0	10.9	9.7	7.0	6.0
AU385	8.0	7.2	6.6	2.9	7.9	5.2	1.8	2.1	12.2	2.2	2.4	38.5	6.9	10.8	9.9	5.4	6.7	35.4	29.9	20.4	0.1	84.0	9.2	30.8	20.4	2.2	20.0	13.7	11.6	8.5	7.9
AU386	5.7	5.7	5.1	1.8	7.4	3.7	1.4	1.6	10.2	2.0	1.7	33.8	5.2	9.8	3.5	4.7	2.7	30.6	28.0	19.0	0.1	76.8	8.6	28.9	19.3	2.6	19.1	13.1	12.1	8.0	6.6
AU387	6.0	6.0	3.5	2.0	7.0	5.0	1.5	1.5	8.0	2.0	2.0	39.0	2.4	2.8	2.5	2.0	2.4	10.4	20.1	20.3	0.1	21.7	3.9	7.0	5.1	1.0	5.0	3.5	3.0	3.0	1.7
AU388	9.5	7.4	3.9	1.5	4.4	3.2	1.0	0.9	25.0	1.6	1.6	92.0	2.0	65.9	2.0	6.8	0.5	184.0	97.6	56.3	1.0	422.9	67.6	129.9	99.4	9.0	81.3	62.4	43.7	35.0	27.1
ID118	12.3	17.0	26.8	9.3	40.5	28.6	11.1	13.4	28.8	10.8	9.9	47.3	6.9	45.2	5.7	3.0	5.5	138.2	49.1	21.5	69.0	195.2	17.0	96.9	70.4	7.5	70.6	47.5	45.1	28.3	29.8
ID119	15.5	21.1	29.8	11.2	47.0	32.2	12.2	12.7	41.8	10.2	10.2	55.8	8.0	63.4	1.6	8.3	1.9	153.4	61.3	31.1	57.7	256.5	18.7	117.4	84.4	1.9	92.9	62.2	54.4	34.9	37.1
ID120	24.4	33.1	42.7	16.1	68.6	47.5	19.2	21.0	77.8	15.3	15.2	98.6	14.3	131.9	2.5	23.5	8.2	316.9	123.9	65.4	94.1	520.4	44.2	253.6	186.0	17.8	193.6	135.1	119.7	81.4	82.6
ID122	8.3	11.5	16.0	5.0	21.2	15.1	5.8	5.5	16.1	5.1	5.1	12.6	0.4	12.2	0.7	1.3	0.2	24.0	8.2	12.1	2.1	37.5	4.0	16.2	12.2	0.7	11.4	7.6	6.1	4.2	4.1
ID123	16.0	19.7	27.6	9.0	41.5	31.0	12.4	12.8	34.6	10.4	11.6	31.2	5.0	38.0	2.2	3.7	1.5	73.5	25.9	30.3	2.2	123.8	16.0	61.2	44.5	9.4	42.5	29.0	25.4	16.0	19.4
ID139	15.3	20.4	13.7	12.3	50.3	22.4	11.6	9.4	184.5	7.8	7.9	45.7	2.9	295.3	6.5	2.8	3.5	808.5	68.0	1.8	5.5	454.6	34.4	231.0	198.5	29.8	127.6	85.7	93.2	58.6	82.8
ID157	6.4	3.0	2.6	0.8	1.5	0.8	0.1	0.2	1.2	0.2	0.2	0.9	0.1	1.5	0.1	0.1	0.1	4.2	0.9	0.3	0.0	6.4	0.8	1.9	1.9	0.1	1.4	1.1	0.8	0.5	0.5
ID176	62.2	68.3	42.0	35.5	143.6	57.5	24.7	21.5	345.9	16.5	19.2	59.6	5.3	209.8	7.1	1.8	3.1	536.1	63.1	2.9	3.4	300.0	24.5	127.1	103.8	18.3	70.7	47.9	52.4	33.1	43.3

Biomarker ppm Data
(relative to branched/cyclic HC fraction)

SampleID	C34S	C34R	C35S	C35R	S1	S2	S3	S4	S4B	S5	S5B	S6	S7	S8	S9	S9B	S10	S10B	S11	S12	S13	S13B	S14	S14B	S15
AU001	12.9	8.4	5.7	4.0	77.5	45.3	8.1	76.6	52.8	20.2	32.1	17.7	38.1	4.1	12.2	21.0	19.9	26.8	7.1	16.5	28.5	47.9	25.5	44.9	20.0
AU002	26.0	17.9	11.8	8.4	76.6	45.4	26.0	88.5	74.0	32.2	51.5	37.4	43.8	9.3	22.1	37.5	34.3	47.2	17.3	36.6	50.3	84.8	43.7	77.9	44.9
AU003	6.2	4.5	3.3	2.2	33.5	20.3	5.8	27.1	20.9	8.8	13.3	21.7	14.0	2.8	7.1	9.0	7.5	11.0	8.9	6.0	11.1	17.0	8.8	14.7	17.2
AU021	17.5	11.5	11.5	7.8	6.8	3.9	3.1	48.7	18.8	3.2	4.2	7.2	29.3	3.1	7.8	13.1	11.8	17.1	7.8	15.8	24.4	38.4	21.1	37.5	22.6
AU027	3.4	2.2	2.2	1.3	10.7	6.3	1.5	11.9	8.0	3.0	4.8	3.4	6.2	0.6	1.9	3.2	3.4	4.9	1.7	4.1	5.1	8.2	4.3	7.5	5.2
AU028	3.7	2.6	2.0	2.0	12.5	7.0	1.4	13.0	8.4	1.3	4.9	3.5	7.0	1.3	2.2	3.6	3.8	4.9	2.1	4.5	7.0	9.0	5.0	7.7	8.0
AU029	0.8	0.5	0.4	0.6	8.2	4.8	1.8	8.4	6.6	3.5	5.0	2.5	4.6	0.9	1.7	2.6	3.5	4.2	0.6	2.5	4.8	7.0	3.8	6.1	3.0
AU030	3.4	1.8	2.9	2.1	25.8	14.6	5.1	24.9	20.3	10.1	15.4	7.4	14.9	2.4	5.0	7.6	12.0	13.3	3.1	8.7	14.4	20.9	11.1	18.9	9.5
AU031	3.6	2.5	4.1	2.6	26.9	15.1	5.5	27.0	22.8	10.8	15.7	7.8	15.3	2.2	5.1	8.4	12.2	13.9	3.1	9.0	15.1	22.7	11.8	19.8	10.2
AU032	5.6	3.2	5.1	3.7	39.6	23.9	7.6	46.7	33.9	16.7	24.4	12.4	32.0	3.9	8.2	12.5	25.4	26.3	5.1	16.0	22.4	33.3	18.1	30.3	17.6
AU033	20.2	11.3	21.4	12.9	101.8	61.4	38.0	119.8	93.2	47.9	73.7	34.3	79.5	10.3	22.1	35.4	71.5	76.5	14.3	55.6	68.1	100.9	61.6	103.3	45.7
AU034	2.8	1.7	2.4	2.5	14.1	8.9	5.4	17.9	17.0	8.2	12.7	5.9	9.1	1.4	4.2	6.8	7.6	9.0	2.1	5.8	11.4	17.6	9.4	15.8	7.4
AU035	5.4	3.9	2.9	0.8	12.2	7.0	4.2	13.4	12.3	7.0	8.7	11.2	6.6	2.5	3.8	6.4	5.7	7.8	4.8	7.5	8.6	13.6	7.3	12.4	11.9
AU036	23.0	14.0	9.5	7.4	45.2	28.2	11.3	53.2	43.8	20.2	30.0	25.9	30.1	6.6	13.1	21.6	21.0	28.2	11.6	26.4	30.9	50.7	25.3	45.0	31.3
AU037	26.8	17.2	11.3	9.1	56.8	35.0	13.4	65.5	51.7	23.2	35.3	29.8	35.7	7.7	15.2	25.9	25.7	34.6	13.6	31.2	34.3	56.5	30.9	54.8	38.7
AU038	25.6	17.6	11.5	8.0	53.3	34.2	12.9	59.2	48.8	23.5	35.1	28.5	33.6	8.3	15.1	24.9	26.2	34.7	12.9	28.7	36.1	57.5	30.2	50.2	35.1
AU039	27.2	18.9	11.5	9.0	56.2	36.4	21.2	64.5	53.0	23.9	37.1	32.0	36.2	8.3	15.1	25.8	25.7	34.3	14.3	33.9	36.9	59.6	31.8	55.4	39.3
AU040	8.2	5.6	3.9	3.0	38.3	24.4	4.0	37.9	25.9	11.2	16.0	9.8	21.2	3.0	6.5	11.0	10.8	13.9	3.8	9.0	15.3	24.2	12.2	21.5	11.8
AU041	6.6	4.6	3.0	2.0	28.0	17.5	8.0	29.9	19.2	9.3	11.8	7.4	18.2	1.7	5.4	8.7	8.7	11.3	3.6	7.8	13.8	19.5	9.7	17.0	10.1
AU042	7.4	4.7	3.2	2.3	34.9	22.3	3.8	34.8	24.3	10.1	14.7	8.8	19.4	2.4	5.6	9.5	10.0	13.0	3.6	8.5	14.0	22.1	11.8	20.0	11.0
AU043	14.8	10.2	6.4	5.1	28.8	17.5	7.8	32.9	28.5	13.0	19.2	23.0	17.9	4.6	8.7	14.2	12.3	17.4	10.2	17.7	20.5	32.6	17.0	28.3	27.1
AU044	26.4	18.0	12.3	9.8	56.9	35.2	13.9	66.6	53.1	26.6	37.9	31.6	36.3	8.4	17.6	27.4	26.5	34.3	13.4	31.1	38.9	59.5	33.0	54.5	36.6
AU045	8.2	6.0	3.7	3.0	25.8	15.8	6.0	26.8	19.8	10.2	13.7	14.1	13.7	3.3	6.0	9.3	9.3	11.8	5.3	9.4	12.7	18.9	10.7	17.0	13.2
AU046	9.3	6.3	4.2	3.3	31.6	18.8	7.7	31.5	24.0	11.7	16.5	16.7	16.5	4.2	7.5	11.6	11.7	14.8	6.8	11.8	15.5	23.6	13.2	20.8	17.0
AU047	5.6	4.1	3.4	1.7	21.3	12.7	4.6	21.3	16.7	8.2	11.5	11.1	11.2	2.5	5.1	7.8	7.9	10.0	4.6	7.5	10.5	16.5	8.3	13.5	11.2
AU048	4.6	3.3	2.1	3.1	16.5	9.6	3.5	15.9	12.5	6.2	8.5	8.5	8.5	2.1	3.8	5.9	5.9	7.8	3.0	5.4	8.2	12.6	6.7	11.1	7.7
AU049	0.6	0.1	0.5	0.2	1.0	0.5	0.4	1.1	1.2	0.7	0.9	0.6	0.4	0.2	0.4	0.6	0.4	0.7	0.2	0.5	0.8	1.3	0.6	1.1	0.6
AU050	1.9	1.2	2.3	1.8	2.1	1.4	2.0	3.9	5.0	2.6	4.2	2.7	1.3	0.6	1.2	2.2	1.5	2.4	0.7	1.8	3.7	5.6	2.9	4.9	2.5
AU051	0.9	0.8	0.7	0.5	4.4	2.5	1.1	4.1	4.0	1.8	2.8	2.4	1.7	0.5	1.1	1.8	1.3	2.1	0.7	1.3	2.0	3.3	1.7	2.9	1.8
AU052	6.4	4.5	4.9	4.2	15.4	9.6	3.9	18.2	15.9	8.2	11.4	9.4	8.9	2.3	5.5	8.0	7.2	9.8	4.5	8.2	11.8	16.8	9.4	14.7	11.5
AU053	3.4	2.2	3.3	2.3	2.5	1.4	0.6	1.6	1.4	0.8	1.1	0.7	0.7	0.2	0.6	0.9	0.7	1.0	0.3	0.7	1.3	2.1	1.1	1.8	1.1
AU054	4.7	3.7	2.1	2.9	17.4	11.0	1.9	17.6	12.3	6.1	8.4	4.6	10.0	1.5	3.4	5.2	5.3	6.8	1.9	5.0	7.4	11.2	6.2	10.0	5.2
AU055	7.1	4.9	3.2	0.8	25.8	16.3	6.6	27.0	19.0	10.3	12.8	7.0	14.8	2.7	5.0	8.0	8.4	10.7	3.1	7.8	11.0	17.0	9.7	15.9	8.2
AU056	0.3	0.3	0.4	0.3	4.1	2.8	1.1	4.1	3.8	1.9	2.7	5.8	2.1	0.7	1.4	1.9	1.7	2.4	2.9	1.6	2.8	4.1	2.1	3.5	4.5
AU057	0.3	0.3	0.4	0.4	0.2	0.1	0.0	0.2	0.2	0.1	0.2	0.1	0.1	0.0	0.1	0.1	0.1	0.2	0.1	0.1	0.1	0.2	0.1	0.2	0.2
AU058	1.4	0.2	0.3	0.3	4.0	2.4	0.5	4.2	2.6	1.2	1.6	1.4	2.5	0.5	0.9	1.2	1.3	1.6	0.8	1.7	2.1	2.7	1.4	2.3	2.7
AU059	3.2	2.2	1.8	1.9	2.7	1.5	0.6	8.6	3.4	1.7	1.3	2.0	6.0	1.0	1.6	2.4	3.0	3.4	1.1	3.6	5.7	7.8	4.3	6.8	4.5
AU060	17.1	10.8	7.2	5.7	15.4	9.4	12.9	25.0	23.0	11.9	16.4	30.5	13.6	7.4	10.0	14.7	14.7	19.0	15.4	27.8	27.0	36.5	20.3	32.0	48.6
AU061	2.3	1.7	1.0	0.7	6.3	3.3	1.2	7.0	5.1	2.3	3.3	2.8	3.8	0.9	1.9	2.7	2.5	3.3	1.4	3.1	3.8	5.7	3.0	4.8	3.9
AU062	0.2	0.1	0.2	0.4	0.7	0.4	0.1	0.5	0.5	0.2	0.3	0.2	0.2	0.1	0.5	0.5	0.2	0.3	0.1	0.1	0.3	0.4	0.2	0.3	0.2
AU063	3.5	0.4	1.4	0.5	7.2	4.0	1.6	8.9	7.5	3.8	5.3	4.8	5.2	1.8	2.8	4.5	4.6	6.1	2.7	2.8	7.1	10.6	5.4	9.2	7.7
AU064	4.0	0.5	1.9	0.6	8.3	4.9	2.2	10.4	8.5	4.2	5.8	5.6	6.0	1.2	3.1	4.8	5.1	6.5	2.8	7.0	7.4	11.8	5.9	9.9	8.5
AU065	3.7	2.8	2.1	1.3	7.7	4.2	2.3	9.5	7.8	3.8	5.5	4.7	5.5	1.7	3.0	4.4	4.7	6.0	2.7	6.9	7.0	10.5	5.6	9.5	7.7
AU066	0.5	0.4	0.6	0.3	6.3	3.5	0.5	5.0	3.0	1.2	1.7	1.0	2.8	0.4	0.8	1.2	1.2	1.5	0.5	1.2	1.7	2.4	1.2	1.9	1.2
AU067	14.1	8.8	6.9	4.5	50.7	31.9	6.6	51.1	40.6	17.8	26.6	14.7	27.8	4.2	11.0	18.3	16.5	21.7	5.7	14.5	22.0	35.6	17.3	29.2	15.5

Biomarker ppm Data
(relative to branched/cyclic HC fraction)

SampleID	C34S	C34R	C35S	C35R	S1	S2	S3	S4	S4B	S5	S5B	S6	S7	S8	S9	S9B	S10	S10B	S11	S12	S13	S13B	S14	S14B	S15
AU068	10.8	7.2	5.2	3.8	42.8	28.1	4.9	43.8	33.0	14.9	22.3	11.9	23.5	3.2	8.7	14.3	13.2	18.0	4.6	13.0	17.3	28.1	15.0	24.8	12.5
AU069	10.5	6.9	4.0	2.6	43.1	26.4	5.6	41.8	32.7	13.8	20.8	11.1	21.8	3.0	8.5	13.4	12.7	17.0	4.5	12.2	17.0	26.9	14.5	24.8	12.3
AU071	12.3	6.4	5.4	2.3	22.2	12.5	7.1	27.6	25.4	12.5	18.7	13.5	15.4	4.8	9.3	15.0	16.1	20.8	2.3	1.8	23.9	37.9	19.0	33.1	20.2
AU072	0.3	0.3	0.4	0.3	0.6	0.3	0.2	0.6	0.4	0.2	0.3	0.2	0.4	0.1	0.5	0.5	0.3	0.4	0.0	0.2	0.3	0.5	0.3	0.4	0.3
AU073	9.3	5.3	5.1	4.6	20.5	12.5	7.3	25.9	24.2	11.7	18.3	17.7	13.9	4.2	8.7	13.5	14.0	18.8	9.6	16.7	21.0	31.4	15.9	26.8	23.7
AU074	10.2	6.8	4.0	1.6	19.8	12.1	7.4	29.7	27.0	12.8	19.4	13.4	16.1	4.6	10.1	16.1	15.5	20.2	6.8	18.9	22.3	36.4	18.9	33.1	20.6
AU075	0.3	0.3	0.3	0.5	5.0	2.6	1.0	3.5	3.3	1.5	2.5	1.4	1.2	0.4	0.8	1.1	0.8	1.1	0.4	0.8	1.2	2.0	1.1	1.7	0.7
AU076	0.5	0.5	0.5	0.5	1.2	0.6	0.2	0.9	0.6	0.3	0.3	0.4	0.4	0.1	0.3	0.3	0.2	0.3	0.1	0.3	0.3	0.4	0.2	0.4	0.4
AU077	0.5	0.6	0.5	0.4	1.4	0.8	0.2	1.0	0.7	0.3	0.4	0.4	0.5	0.1	0.4	0.5	0.3	0.4	0.2	0.4	0.4	0.6	0.3	0.4	0.4
AU078	1.3	0.4	0.6	0.6	4.1	2.2	0.9	4.5	3.2	1.6	2.2	2.5	2.6	0.6	1.2	1.9	1.2	2.2	1.2	2.4	3.0	4.1	2.0	3.4	3.0
AU079	0.5	0.1	0.3	0.4	0.4	0.2	0.2	0.5	0.5	0.3	0.4	0.2	0.2	0.2	0.5	0.6	0.2	0.6	0.2	0.2	0.3	0.6	0.3	0.5	0.3
AU080	13.1	8.9	6.8	4.7	23.8	14.3	14.3	34.8	32.5	15.3	22.5	20.7	19.5	5.9	11.4	18.8	18.9	25.0	10.6	24.9	28.2	43.5	21.8	37.4	30.4
AU081	5.0	3.5	2.9	2.3	24.2	13.9	4.1	24.7	20.9	9.5	13.9	8.8	13.7	2.7	6.4	10.7	10.4	13.3	3.8	9.5	13.1	21.1	10.6	18.0	10.8
AU082	5.9	4.2	2.5	2.3	24.9	15.0	4.4	26.5	22.2	10.4	15.5	9.3	14.1	2.9	6.5	10.6	9.9	13.2	4.1	10.2	13.4	21.5	11.3	18.8	10.9
AU083	5.6	3.6	3.0	1.9	26.5	16.2	4.0	27.7	22.3	10.4	14.9	9.5	14.7	2.6	6.4	10.9	10.2	13.5	4.3	10.2	14.2	22.6	11.6	20.5	12.0
AU084	6.2	3.8	2.7	1.0	27.2	16.7	4.9	27.8	22.8	9.9	15.1	9.4	15.3	2.8	6.8	10.9	10.6	13.9	4.4	10.9	14.1	22.4	11.7	20.1	12.4
AU085	3.7	3.7	2.1	2.2	12.3	7.3	2.0	14.1	9.1	3.8	5.5	4.7	8.4	1.5	2.6	4.1	4.2	5.4	2.6	5.7	6.4	9.2	4.9	8.4	8.5
AU087	3.3	2.3	0.7	0.9	8.0	4.5	3.4	10.6	11.9	5.4	9.3	9.7	4.8	1.8	2.8	6.1	4.3	7.7	3.2	5.7	8.2	14.2	6.1	12.1	9.1
AU088	10.6	6.9	7.4	6.1	4.3	1.6	6.3	36.1	12.8	2.5	2.3	2.0	18.7	2.3	4.9	9.3	7.3	12.1	2.7	8.0	14.8	28.8	10.6	24.4	11.1
AU089	7.0	4.6	5.6	3.4	3.1	0.4	4.3	23.4	8.6	1.9	1.6	1.7	12.9	1.3	3.2	5.8	5.1	8.0	2.1	5.6	10.6	19.4	7.6	16.2	7.6
AU090	1.3	1.0	0.4	0.5	3.5	1.9	0.6	4.0	3.1	1.3	2.2	1.6	2.0	0.4	1.0	1.8	1.5	2.2	0.6	1.8	2.3	3.8	1.7	3.1	1.9
AU091	0.2	0.2	0.3	0.3	1.4	0.8	0.3	1.5	1.2	0.6	0.9	0.6	0.8	0.2	0.1	0.6	0.6	0.8	0.3	0.7	0.8	1.3	0.6	1.1	0.6
AU092	1.0	0.4	0.4	0.2	3.0	1.6	0.6	3.3	2.4	1.3	1.7	1.2	1.9	0.4	0.8	1.3	1.2	1.8	0.6	1.4	1.8	3.2	1.5	2.6	1.6
AU093	0.1	0.3	0.1	0.3	2.0	1.1	0.2	1.6	1.0	0.4	0.6	0.3	0.4	0.1	0.4	0.3	0.3	0.5	0.1	0.2	0.1	0.7	0.3	0.5	0.1
AU094	0.1	0.4	0.2	0.3	7.4	4.1	0.5	7.9	4.9	1.7	2.5	1.3	4.2	0.5	1.2	2.1	1.9	3.1	0.7	1.6	2.7	5.2	2.1	4.2	1.7
AU095	0.5	0.2	0.2	0.1	4.8	2.6	0.3	3.9	2.7	0.8	1.4	0.6	2.0	1.0	0.7	1.1	0.9	1.3	0.2	0.6	1.1	2.0	0.8	1.7	0.6
AU096	3.4	2.2	3.0	2.3	2.4	0.2	1.3	3.1	3.2	1.4	2.3	2.9	1.6	0.9	0.6	1.8	1.1	1.9	0.4	1.2	2.2	4.0	1.7	3.5	2.9
AU097	1.9	1.3	0.7	0.6	4.6	2.8	1.0	5.5	4.6	1.7	3.0	3.0	3.1	0.8	1.4	2.6	2.2	3.5	1.6	2.9	3.8	6.5	2.7	5.6	3.6
AU098	0.1	0.2	0.1	0.1	2.6	1.6	0.5	2.8	2.4	0.9	1.6	1.5	1.5	0.4	0.8	1.2	1.0	1.5	0.7	1.3	1.7	2.6	1.1	2.2	1.3
AU099	0.2	0.1	0.1	0.1	2.4	1.3	0.5	2.3	1.8	0.8	1.3	1.1	1.3	0.3	0.5	1.0	0.8	1.2	0.5	0.9	1.2	1.8	0.8	1.6	0.9
AU100	0.7	0.6	0.5	0.6	6.4	3.4	0.8	8.0	4.6	2.0	2.4	1.7	4.8	0.7	1.1	2.0	1.8	2.9	1.1	3.4	2.9	4.7	1.8	3.6	2.9
AU101	2.5	1.8	1.5	1.0	8.6	4.6	1.9	11.8	6.7	2.4	3.8	2.7	6.8	0.9	1.9	3.5	3.0	4.6	1.6	4.8	5.0	8.8	3.6	7.8	6.1
AU102	0.8	0.3	0.2	0.2	6.1	3.5	1.2	7.0	5.6	2.4	3.8	3.1	4.2	0.9	1.6	3.1	2.8	4.1	1.6	3.7	4.3	7.3	3.1	6.0	3.4
AU103	0.7	0.6	0.1	0.3	5.0	2.9	1.0	6.1	4.7	2.0	3.1	2.7	3.5	0.7	1.5	2.6	2.3	3.5	1.4	3.3	4.0	6.5	2.7	5.5	3.6
AU104	1.0	0.8	0.7	0.5	9.7	5.0	1.7	9.6	8.0	3.4	5.4	4.0	5.2	1.2	2.1	3.7	3.2	4.9	1.5	4.1	4.8	7.1	3.1	6.1	3.4
AU105	0.3	0.6	0.3	0.3	5.5	3.1	1.4	5.8	4.5	2.0	3.0	2.3	3.4	0.6	1.3	2.3	2.0	2.8	1.2	2.0	3.1	5.0	2.0	4.0	2.4
AU106	0.5	0.5	0.5	0.7	4.8	2.5	1.3	4.5	3.5	1.5	2.3	1.8	2.6	0.5	1.1	1.5	1.4	2.1	0.7	2.0	2.0	3.2	1.4	2.7	1.6
AU107	0.4	0.6	0.4	1.0	7.2	4.0	1.0	7.6	5.9	2.4	3.8	2.9	4.2	0.7	1.7	2.8	2.5	3.6	1.0	3.4	3.8	6.2	2.5	5.3	3.0
AU108	0.5	0.4	0.5	0.7	4.6	2.9	0.5	4.6	3.4	1.3	2.1	1.9	2.6	0.3	0.9	1.5	1.1	2.0	0.7	1.4	1.7	2.7	1.1	2.1	1.3
AU109	0.1	0.3	0.6	0.3	1.4	0.3	0.1	1.2	0.7	0.2	0.2	0.3	0.2	0.3	0.2	0.4	0.4	0.4	0.2	0.4	0.3	0.2	0.3	0.6	0.2
AU110	0.4	0.4	0.5	0.2	5.5	3.0	0.2	5.6	3.2	1.4	1.9	0.8	3.2	0.5	0.7	1.3	1.4	1.9	0.5	0.9	1.5	2.8	1.3	2.5	0.9
AU111	0.5	0.3	0.5	0.5	6.8	3.8	1.4	6.9	4.3	1.6	2.2	0.9	4.0	2.1	1.0	1.7	1.5	2.5	0.5	1.2	2.2	3.9	1.6	3.6	1.2
AU112	0.8	0.9	0.3	0.9	2.6	1.3	0.6	2.4	1.1	0.4	0.6	0.9	0.9	0.2	1.1	0.2	0.6	0.9	0.4	0.6	0.9	0.6	1.1	0.6	1.1
AU113	0.8	1.1	0.7	1.0	2.1	0.1	0.4	2.6	1.4	0.4	0.7	0.3	1.4	0.1	0.3	0.4	0.3	0.7	0.3	0.3	0.7	0.8	0.3	0.7	0.7
AU114	0.4	0.4	0.3	0.6	5.5	2.9	1.6	8.0	4.4	1.6	2.2	1.4	4.7	0.7	1.3	2.0	2.0	2.7	1.1	2.7	3.1	5.0	1.9	4.1	2.6
AU115	4.0	0.8	1.1	1.4	21.6	12.2	5.9	27.7	22.3	9.8	16.0	14.3	15.9	3.8	7.1	12.5	11.4	17.1	7.1	18.4	19.6	31.9	14.3	27.1	18.8

Biomarker ppm Data
(relative to branched/cyclic HC fraction)

SampleID	C34S	C34R	C35S	C35R	S1	S2	S3	S4	S4B	S5	S5B	S6	S7	S8	S9	S9B	S10	S10B	S11	S12	S13	S13B	S14	S14B	S15
AU116	9.4	5.2	3.8	1.3	17.0	9.7	2.0	19.3	14.8	5.1	9.3	4.5	8.7	2.0	3.5	6.8	5.6	9.1	2.4	6.2	9.2	17.1	5.6	12.2	6.4
AU117	1.7	1.3	0.8	0.5	6.8	3.9	0.7	8.0	6.0	2.3	3.9	1.8	4.3	0.6	1.6	2.8	2.4	3.9	1.0	2.5	3.5	6.3	2.7	5.4	2.2
AU118	1.5	0.9	0.4	0.4	8.3	5.0	0.8	9.3	7.2	3.0	4.5	2.3	5.0	0.7	1.8	3.3	2.7	4.4	0.9	3.1	3.8	6.9	3.0	5.7	2.4
AU119	0.3	0.2	0.4	0.5	7.0	3.7	0.9	6.4	5.7	2.1	3.8	2.3	2.6	0.7	1.3	2.4	1.8	3.1	1.0	1.8	2.5	4.5	1.9	3.8	2.0
AU120	0.9	0.2	0.4	0.4	3.8	2.2	0.4	3.5	2.6	0.8	1.6	0.8	2.1	0.4	0.5	1.2	1.4	1.8	0.5	1.1	1.5	2.5	1.1	2.3	1.1
AU121	0.6	0.7	0.9	0.4	5.6	2.8	0.8	4.6	3.3	1.3	1.9	0.8	2.5	0.3	0.6	1.4	1.1	1.8	0.5	0.7	1.5	2.5	0.3	2.1	0.3
AU122	6.7	3.9	5.2	2.8	13.1	8.4	7.9	20.7	26.4	11.5	22.0	10.7	9.4	4.7	10.2	19.1	13.4	22.5	5.8	11.5	18.1	33.2	13.1	29.3	15.2
AU123	2.1	1.2	1.4	0.9	2.0	1.3	2.2	4.1	5.4	2.8	5.0	2.6	1.8	1.3	2.8	5.1	3.5	5.8	1.7	3.3	5.2	9.0	3.9	7.9	3.8
AU124	3.6	2.3	1.1	0.8	1.2	0.7	0.4	7.6	3.5	1.2	1.2	0.9	5.1	2.0	1.5	2.6	3.5	4.7	1.2	4.6	9.7	15.8	4.5	9.4	6.9
AU125	0.6	0.5	0.4	0.6	0.5	0.3	0.2	2.5	1.4	0.6	0.7	0.4	1.8	0.4	1.1	1.2	1.2	1.7	0.5	0.8	1.7	3.1	1.4	2.3	1.1
AU126	0.7	0.4	0.5	0.6	0.5	0.1	0.1	0.2	0.3	0.2	0.4	0.1	0.3	0.0	0.2	0.3	0.1	0.3	0.1	0.3	0.1	0.3	0.1	0.1	0.1
AU127	0.3	0.4	0.2	0.5	1.0	0.6	0.1	0.8	1.0	0.5	0.7	0.3	0.4	0.1	0.5	0.5	0.4	0.6	0.1	0.2	0.4	0.6	0.2	0.6	0.2
AU128	0.8	0.7	0.5	0.7	2.8	1.7	1.1	2.6	2.8	1.5	2.2	1.1	0.6	0.9	0.4	1.9	1.5	2.1	0.6	0.6	1.7	2.4	0.4	2.2	0.4
AU129	5.2	3.3	3.5	3.0	12.1	6.1	8.8	19.4	24.4	11.9	20.9	11.2	9.0	3.5	9.0	19.2	12.3	21.3	5.4	11.1	15.7	32.2	13.0	27.3	13.3
AU130	6.8	4.6	4.2	2.8	9.8	5.3	10.1	18.6	26.5	13.0	22.7	10.8	7.9	5.0	11.3	22.0	14.0	25.5	6.3	13.3	19.4	36.7	15.7	33.8	16.6
AU131	7.3	4.2	5.3	1.9	7.6	3.2	3.5	17.7	15.4	5.6	9.5	5.2	9.1	2.6	7.1	13.2	9.1	15.6	4.1	9.1	14.1	24.5	10.2	21.2	10.2
AU132	0.2	0.2	0.2	0.4	0.3	0.1	0.2	0.8	0.5	0.3	0.3	0.1	0.4	0.2	0.4	0.5	0.6	0.8	0.2	0.4	0.6	1.0	0.4	0.9	0.4
AU133	1.0	0.3	0.3	0.6	1.6	0.9	1.0	4.7	3.7	1.6	2.5	1.4	2.6	0.3	1.2	1.9	1.2	2.5	0.6	1.8	3.0	6.2	2.5	5.2	1.7
AU134	1.0	0.7	0.7	1.8	5.0	2.7	1.2	5.2	5.8	2.2	4.2	2.0	3.0	0.5	1.8	3.4	2.6	3.9	0.8	1.4	3.3	6.0	2.2	4.7	2.1
AU135	0.2	0.8	0.4	1.3	4.3	2.3	1.5	5.3	5.8	3.0	5.7	1.8	3.0	1.1	2.4	4.5	3.5	5.4	1.2	2.4	4.1	8.3	3.3	7.0	2.7
AU136	1.7	0.5	1.5	1.4	4.4	2.4	0.6	5.5	6.2	3.2	5.3	2.1	3.2	0.9	2.6	4.3	4.0	5.9	1.1	3.0	5.0	8.7	3.2	7.1	3.3
AU137	2.3	1.0	1.7	0.7	4.7	2.9	0.7	6.5	7.2	3.4	5.9	2.2	3.7	1.3	2.9	5.2	4.5	6.9	1.5	2.7	5.2	10.4	3.4	8.6	3.4
AU138	0.6	1.1	0.4	0.7	1.7	1.2	1.2	2.4	3.3	1.8	2.8	0.5	0.7	0.4	1.3	2.4	1.7	2.6	0.4	1.3	1.9	3.9	1.9	3.7	1.7
AU140	13.5	7.7	6.6	5.5	502.8	297.6	486.9	805.0	1253.0	600.8	1176.5	508.6	330.7	149.6	268.9	539.2	404.4	636.7	151.4	393.2	608.0	1153.4	531.9	1119.1	456.4
AU141	10.1	5.9	4.5	3.7	396.6	227.7	370.9	621.8	964.4	460.0	892.1	400.2	263.3	111.0	208.7	423.8	316.5	504.2	117.5	302.4	437.2	861.5	412.5	873.1	349.0
AU142	19.5	12.1	11.6	7.3	28.9	16.8	15.7	40.4	50.6	23.6	40.3	17.0	22.2	7.1	14.2	27.0	22.8	34.7	7.9	20.2	36.3	69.6	28.4	61.9	26.5
AU143	22.1	12.7	12.5	7.9	278.1	167.2	439.3	486.2	830.9	404.3	775.0	523.8	201.5	117.3	156.1	321.6	250.6	397.8	139.2	317.9	348.1	658.6	307.7	653.3	380.8
AU144	11.5	6.6	12.8	7.4	60.4	37.0	13.2	67.1	68.3	23.7	44.0	16.5	30.0	3.8	10.4	19.3	16.8	25.9	4.2	17.0	33.6	61.8	24.1	52.9	20.0
AU145	2.0	1.3	0.6	1.2	17.9	10.1	5.5	19.0	17.4	6.2	11.4	6.1	10.4	5.3	3.7	5.9	5.3	7.8	2.0	6.1	9.5	16.7	6.5	14.2	6.7
AU146	218.6	155.0	76.5	50.0	86.0	49.4	38.5	113.9	133.1	55.3	103.6	36.8	54.2	10.6	22.5	42.1	47.6	72.2	18.6	87.5	96.9	171.3	65.8	158.9	65.1
AU147	0.6	0.5	0.4	0.3	0.8	0.2	0.5	1.0	0.7	0.3	0.7	0.5	0.3	0.3	0.3	0.3	0.1	0.1	0.3	0.2	0.3	1.0	0.4	1.0	0.1
AU148	7.1	4.2	5.3	3.4	44.7	26.6	11.5	48.2	40.2	14.4	27.1	12.2	24.0	4.0	8.0	15.1	13.2	20.5	3.5	11.6	22.8	42.1	17.4	34.7	13.6
AU149	6.2	3.3	5.4	2.8	36.6	22.4	8.7	39.1	32.8	12.6	22.4	9.3	18.6	2.5	6.6	11.8	11.5	16.8	3.2	10.0	19.4	36.4	14.2	30.3	11.5
AU150	14.2	8.5	13.0	7.5	57.7	36.8	15.4	63.2	61.2	21.7	40.1	16.0	29.4	5.0	11.4	21.2	16.3	26.3	4.8	17.2	34.1	63.0	25.5	51.8	19.4
AU151	17.9	11.1	16.1	9.3	90.3	52.9	21.3	95.6	92.1	32.7	62.1	23.6	44.1	6.6	15.7	29.4	25.3	39.5	6.5	25.6	50.2	93.2	36.1	77.9	28.0
AU152	2.2	1.2	0.7	0.3	9.2	5.5	1.8	9.8	8.4	3.2	5.0	2.5	5.2	0.7	1.9	3.8	3.2	4.7	1.2	0.0	4.5	8.0	3.6	7.2	3.0
AU153	12.3	7.9	5.2	4.1	15.0	8.6	8.5	20.3	22.9	9.8	16.9	13.9	11.1	3.4	7.0	13.7	11.1	17.5	6.7	16.7	17.6	32.1	13.6	28.3	20.9
AU279	1.6	1.2	1.2	0.4	2.0	1.3	0.5	3.3	1.9	0.9	1.2	0.7	1.8	0.3	0.4	1.0	0.9	1.3	0.3	1.0	1.3	2.5	1.0	1.8	0.7
AU328	1.0	0.5	0.5	0.5	4.0	2.0	1.0	5.0	5.0	2.0	3.0	4.0	2.0	1.0	1.0	2.0	2.0	3.0	1.0	3.0	3.0	5.0	2.0	4.0	4.0
AU329	6.0	3.0	2.0	1.5	167.0	107.0	179.0	315.0	488.0	242.0	452.0	192.0	126.0	53.0	107.0	207.0	175.0	272.0	58.0	159.0	266.0	506.0	240.0	474.0	195.0
AU338	25.7	18.7	9.3	7.6	26.4	16.3	7.3	38.1	28.9	11.5	17.1	38.5	24.3	7.2	9.3	17.5	10.9	20.7	21.1	31.6	31.0	50.4	16.4	38.6	69.4
AU351	2.9	1.6	2.8	3.3	18.8	11.2	4.2	15.8	14.0	7.2	11.2	5.4	12.0	2.0	3.9	5.8	9.3	9.3	1.6	6.0	11.5	15.3	8.2	13.7	7.6
AU352	0.6	0.5	0.5	0.2	8.5	6.0	1.4	6.9	5.8	3.7	4.4	2.8	5.2	0.9	1.9	2.4	3.3	3.4	0.9	2.2	4.4	5.5	3.1	4.7	2.9
AU353	0.2	0.1	0.1	0.1	0.7	0.4	0.2	0.8	0.4	0.3	0.3	0.2	0.6	0.1	0.2	0.3	0.3	0.3	0.1	0.3	0.4	0.5	0.3	0.5	0.3
AU360	28.6	41.3	28.6	34.9	14.4	12.2	2.2	10.0	7.8	6.7	3.3	5.6	6.7	5.6	3.3	3.3	3.3	5.6	2.2	4.4	3.3	5.6	5.6	2.2	2.2
AU362	5.8	5.0	8.9	7.8	21.7	12.1	2.6	14.5	12.4	5.8	9.0	1.7	9.2	5.5	3.2	6.4	6.4	6.9	2.9	5.5	7.2	11.6	5.5	9.8	3.5

Biomarker ppm Data
(relative to branched/cyclic HC fraction)

SampleID	C34S	C34R	C35S	C35R	S1	S2	S3	S4	S4B	S5	S5B	S6	S7	S8	S9	S9B	S10	S10B	S11	S12	S13	S13B	S14	S14B	S15
AU363	1.2	1.1	3.7	2.5	0.5	0.4	0.6	1.3	1.2	0.5	1.0	1.2	0.3	0.4	1.5	1.3	0.8	0.9	0.6	0.8	1.0	1.3	6.8	2.5	0.5
AU366	18.2	25.6	38.4	35.0	13.2	7.5	1.9	4.7	1.9	1.9	2.8	5.7	4.7	2.8	2.8	5.7	5.7	4.7	3.8	2.8	1.9	2.8	1.9	2.8	2.8
AU367	6.5	2.5	1.7	4.8	5.7	3.9	3.5	8.1	8.6	6.3	7.7	5.3	5.2	2.4	5.6	7.2	8.6	9.7	2.9	6.2	9.9	13.6	9.0	13.1	8.0
AU368	7.9	12.3	5.5	12.3	2.3	1.0	1.0	2.3	3.6	1.3	3.6	1.0	1.0	1.6	1.3	3.2	2.6	2.6	1.6	1.3	2.9	3.2	2.3	1.3	1.0
AU369	1.5	2.7	2.4	2.7	4.0	3.4	0.6	4.1	3.9	1.3	3.0	0.7	1.5	0.5	2.6	3.2	3.4	4.1	0.9	2.0	3.6	5.2	3.3	4.6	2.6
AU370	12.3	9.4	5.3	4.5	17.6	12.0	6.8	21.4	21.6	11.8	16.6	13.3	14.8	4.2	9.4	13.0	14.1	18.5	6.2	21.3	26.7	33.5	19.8	30.2	21.5
AU371	20.3	12.6	9.2	6.6	22.2	15.3	10.8	28.8	29.0	15.7	22.9	20.6	20.2	5.2	12.5	19.3	20.5	24.6	11.5	31.1	35.1	47.7	27.0	41.8	36.8
AU374	5.8	3.5	3.1	2.7	15.3	9.2	4.3	15.1	14.4	7.2	9.9	8.4	10.1	2.4	5.7	8.4	8.0	10.2	4.0	10.2	14.4	18.5	10.4	16.9	11.2
AU382	10.8	5.1	15.6	13.7	2.2	1.3	1.8	1.3	2.2	1.8	1.8	1.8	2.2	1.8	0.9	2.2	1.3	1.8	1.8	1.8	1.3	2.7	2.2	2.2	1.3
AU383	2.3	1.0	2.0	1.0	17.9	10.4	3.8	13.8	13.4	6.8	10.0	4.7	8.0	1.4	3.9	7.0	6.5	7.6	2.2	6.0	8.6	11.9	7.2	10.8	5.0
AU384	6.0	4.0	1.7	1.0	36.1	3.2	6.1	27.9	22.6	13.3	17.3	9.5	18.4	3.8	8.4	12.6	12.3	15.8	4.0	12.4	18.9	24.7	14.9	22.6	11.2
AU385	7.9	5.0	3.0	1.0	32.2	21.2	9.1	27.3	24.7	13.8	18.6	10.4	18.4	3.1	8.6	13.7	13.4	17.4	4.4	14.7	20.3	26.8	15.5	24.8	14.5
AU386	6.6	4.2	5.2	1.1	29.8	19.5	4.4	24.8	23.0	12.9	16.8	8.5	15.2	2.5	7.3	11.6	11.2	14.3	3.6	10.9	15.8	22.5	13.5	21.1	11.2
AU387	1.7	1.4	1.3	1.1	18.0	4.2	2.2	20.1	16.3	9.4	11.0	3.8	16.3	2.7	6.3	9.4	14.0	15.2	3.5	12.7	15.7	23.5	14.5	22.9	9.5
AU388	27.1	18.5	10.7	7.3	21.4	14.8	11.6	26.7	17.8	9.4	13.3	36.5	20.7	3.6	8.5	12.7	11.1	15.9	17.9	30.8	26.3	33.9	20.5	30.3	66.5
ID118	29.8	19.2	28.1	18.7	34.8	20.4	15.8	41.6	44.4	21.6	34.2	18.7	16.7	6.6	14.8	26.0	19.9	31.2	9.4	16.9	26.7	43.7	22.8	40.6	20.2
ID119	37.1	25.0	32.3	20.4	31.9	19.8	14.2	41.2	42.7	19.3	31.8	17.1	16.5	6.8	12.6	22.5	16.6	26.3	8.1	17.3	22.8	42.5	21.3	37.3	18.0
ID120	82.6	53.1	65.6	41.2	54.2	32.1	25.8	76.5	80.3	36.6	60.0	28.3	29.4	12.4	22.3	39.3	28.6	46.2	14.0	37.4	43.9	82.9	41.2	73.6	35.7
ID122	4.1	2.6	2.5	1.5	28.4	16.5	9.7	35.5	31.8	13.9	23.1	10.9	17.6	3.6	8.6	14.3	16.5	21.4	4.6	12.7	21.9	37.7	19.3	32.9	14.7
ID123	19.4	12.8	13.6	10.0	64.3	38.7	29.3	84.7	81.6	38.9	62.1	30.7	42.5	9.7	21.0	36.8	43.3	57.2	14.4	38.2	65.1	101.4	50.1	89.7	42.8
ID139	82.8	55.5	82.1	57.0	6.4	3.6	31.9	50.9	87.5	41.3	73.6	61.5	9.0	17.6	32.4	62.5	38.5	70.6	19.7	47.4	79.5	133.0	67.5	118.5	53.3
ID157	0.5	0.3	0.4	0.3	1.1	0.4	0.2	1.2	0.7	0.3	0.4	0.4	0.5	0.1	0.2	0.4	0.3	0.4	0.2	0.4	0.5	0.7	0.4	0.6	0.5
ID176	43.3	29.9	40.7	28.5	12.1	6.6	32.7	58.3	108.3	41.7	82.9	58.6	13.1	15.3	26.4	66.8	34.4	76.6	17.1	37.5	69.0	135.8	53.5	112.5	45.2

APPENDIX C

C7 Light Hydrocarbon Data

C7_DATAcopy.XLS

SampleID	N-C6	2,2-dimethyl pentane	methylcyclo pentane	2,4-dimethyl pentane	2,2,3-trimethyl pentane	benzene	3,3-dimethyl pentane	cyclo hexane	2-methyl hexane	2,3-dimethyl pentane	1,1-dimethyl cyclopentane	3-methyl hexane	1 cis 3-dimethyl cyclopentane	1 t 3-dimethyl cyclopentane	1 t 2-dimethyl cyclopentane	nC7	methyl cyclohexane	toluene	Total Area
AU029	154549	11604	144044	18555	4869	36396	12132	317275	150330	42198	28703	178462	56615	51604	106022	414418	847473	348659	89267544
AU030	163604	16967	39824	32352	10637	3429	16791	75692	198160	65204	19582	229275	43165	38198	84747	581890	613275	14681	88448624
AU031	1304615	72176	191473	126702	19868	1055	42813	277275	842022	226462	66462	911473	165187	143262	293275	2301538	1867253	16264	122108560
AU032	378286	47736	150286	74901	20000	1502	44923	196571	351648	137670	49495	421451	104967	97319	190330	709407	1088088	8176	88656784
AU034	135824	4659	94330	11956	2057	21099	7736	199033	108484	32791	36571	121319	48352	45978	85890	360352	567692	171253	89592088
AU035	1807824	119912	1278418	154813	43429	67404	67429	1642901	984879	269714	167648	974769	313407	311297	573363	2337231	5307692	945099	132225320
AU036	882022	34989	691385	63824	14945	63560	22593	1020571	407209	105670	86418	416000	209231	160005	304352	1295033	2715488	363516	110423776
AU037	859077	31824	650725	60747	13538	64298	21363	922901	364835	98110	80264	374505	156835	143297	277890	1134681	2369582	406505	92652312
AU038	1147341	45890	868484	71516	23077	73582	29978	1260923	475077	127385	103736	500571	212396	199824	371253	1509714	3202198	438242	134430272
AU039	1242813	58374	977319	89934	27868	52132	37714	1406066	555780	161670	111121	581451	229802	216484	430374	1783033	3634725	321407	159267568
AU040	1408088	61451	933231	90637	18637	75560	31868	1263824	555429	161143	114022	567648	214769	201231	358154	1613538	3156220	401319	145050160
AU041	1306286	56703	892747	85363	19956	78593	35429	1236000	559736	143824	117011	557802	217582	203341	358593	1649934	3249582	426022	161661680
AU042	1426022	54681	956484	92659	20396	81758	39297	1323516	588396	172835	122066	612571	231165	219253	386901	1772659	3466813	419868	169913840
AU043	2643429	104791	892484	215824	27868	37978	54769	925451	1224967	275516	132835	1186462	349890	392352	638989	3018549	3190066	195560	133125464
AU045	1184132	47736	892220	72879	12044	362813	27341	1358301	448967	136352	122725	479473	223736	208615	382418	1341802	3034022	964747	140846496
AU046	1278593	43253	920088	64615	9758	460044	13836	1310523	438505	115604	106813	458637	204571	192703	351912	1409231	2849407	1145934	111502928
AU047	1325538	45626	952967	65495	14637	504835	14134	1386330	448372	122083	117217	462725	211165	201758	356835	1417802	2975736	1197011	117544336
AU048	2701335	101099	1858022	159736	48088	924747	47473	2536527	885011	215121	212220	878462	390593	367575	653934	2664703	5188000	2122286	172635104
AU051	4323692	86681	3121143	215209	26725	596308	51077	3953055	1466110	445890	379429	1592176	813890	758418	1432000	5109275	8738197	2351648	143580672
AU052	5161325	100484	3624967	221582	18374	732308	50110	4388484	1553231	470769	387956	1665934	850462	793582	1482637	5472615	9026505	2806681	140358240
AU054	4216088	116044	1990066	220484	33319	38330	66198	2635560	1348659	328088	254505	1297758	503560	471473	850286	4084835	6999033	527209	158764960
AU055	3697758	92571	1708308	214066	71912	91165	97231	2383736	1173011	301187	224176	1151648	442198	409231	737758	3718593	6176088	335560	137427488
AU056	12308	2989	3604	11516	4396	5363	2769	8176	6589		5538	1758	4835	3165	3253	8000	26901	10725	120416784
AU058	2443956	173187	677363	270242	72440	62505	87385	704923	1596571	332000	332000	1461363	305934	282198	525978	3977363	3311385	170022	127715104
AU059	1274198	36835	503824	84659	11077	16527	25407	746901	623121	158505	66901	585143	192352	174505	299692	2032879	2818637	92835	132060928
AU060	1282637	89407	568000	141978	24879	26462	49670	635604	985582	267253	114989	992440	310242	284659	561582	3304440	2873670	249495	169574160
AU061	1444747	65407	959209	104440	32352	30198	47736	1316308	728440	184703	140835	734330	267429	257055	467868	2185187	4113319	341451	130102600
AU062	3382593	122374	2462154	196484	36132	552352	66286	3593846	1408967	375648	342330	1487824	643077	617407	1156308	4604396	9297494	3737231	133197104
AU063	1136088	72879	931253	98989	23033	34022	34462	1202198	525714	160967	97802	557275	229802	213231	396358	1519385	3381275	341538	135165856
AU064	721670	33582	615648	54593	13714	39648	33670	844571	382154	110945	118857	404132	162110	156220	286769	1105407	2546022	246945	112017488
AU065	1229275	60220	1047121	84044	24967	40264	44747	1360791	592440	177846	129846	611253	258549	242549	439824	1642198	3771604	370549	151637344
AU066	11868	6242	4308	17670	9846	5363	2135	2813	4220		7473	62242	2198	3516	6945	5275	5451	1846	127214184
AU067	3537407	76659	1983209	181890	20308	157714	53758	2526066	1034462	254681	217934	1036659	426286	402022	712264	3301978	5237363	989451	139511888
AU068	2690901	63033	1502198	132044	14242	120000	29231	1905055	803604	210022	175912	813714	326330	304352	548791	2604835	4102505	771429	109424336
AU069	4024088	79121	2262242	201626	22330	186901	39121	2870681	1198769	298022	245978	1183560	472703	448308	803868	3797099	5986462	1158681	154214752
AU071	14764	7209	19956	6505	5187	2110	967	9846	1846		3385	4044	6769	3341	2198	19429	10989	6505	108493712
AU072	1114813	90901	881231	122462	38593	615033	69099	1352615	827780	195956	195956	820747	264440	254857	457758	2079209	4988396	5504791	125775328
AU073	875516	91780	945143	139341	31560	77714	54374	1333626	515165	263385	196923	657319	311560	290637	545055	781187	2562198	245626	136148192
AU074	59604	6154	51165	11516	2198	13275	4132	128044	58637	26813	26813	64967	38945	34901	68747	208703	620396	136000	118300128
AU075	12352	1363	9341	3429	2462	9143	4659	16088	28044	7473	5538	14681	8246	5958	13978	66989	101099	63033	121817848
AU076	5517099	269451	3304879	391209	89846	216967	201143	4413275	2270242	600352	411516	2260747	706286	661363	1229890	5122549	9731956	1484571	162412688
AU077	5738110	275516	3237011	376967	87121	233846	145319	4394022	2409319	581802	400264	2357451	400264	691077	1266198	5725187	10391648	1947077	162672800
AU078	7200088	300308	3305231	489890	106110	130725	171604	3737055	2986989	754198	511736	2819736	1017758	925011	1730462	6843429	11884747	921846	185328208
AU079	4968264	318857	3120703	506901	142242	161758	217978	4131780	3042901	868747	506286	3006593	1043868	963604	1707956	6366329	14198065	1926330	192700448
AU080	7121	2110	11341	7033	9319	4923	4132	2462	16088		16527	923	3692	3516	5099	16264	6857	7560	123742880
AU081	528000	20571	466725	35692	13626	127560	13714	730462	220659	61099	68571	242110	128176	117890	217582	801758	2035868	973187	137352784
AU082	792352	29538	660132	43341	7473	157187	20484	960440	301626	82110	85538	314198	158857	153538	281407	1029846	2482989	1058286	134545360
AU083	244923	10989	247560	21451	8703	85626	6505	449494	145846	41319	43429	173626	92396	81495	156571	616703	1638154	893538	131308792
AU084	243121	19165	269011	29626	14945	98462	17758	486330	160176	47033	47824	184088	90110	93094	160000	657934	1669978	920088	137326016
AU085	2462	5451	879	4097	3868	2989	7736	3780	3692		3253	4571	5363	9275	5978	8176	4044	7385	128421048
AU087	294769	32352	288088	37846	12923	5216	29451	474989	296879	87385	63736	316659	120088	115604	227692	891077	1942418	158154	139573024
AU090	2287560	89055	1481231	146022	33055	44747	59956	1914110	1049670	260923	189538	1071560	386725	364923	664264	3138549	5643780	455341	170805872
AU091	2262418	88527	1377934	146549	37890	44835	62505	1816352	1071121	251516	185714	1065319	380396	361495	654593	3052659	5465758	441582	165223424
AU092	2008703	93187	1120703	152088	32176	30945	60396	1399648	972484	239560	152879	981978	311297	290022	534242	2682549	4390242	330462	126758664
AU093	3212308	123341	2330022	220571	44923	243868	85187	3698813	1521055	375121	333451	1468835	603517	567473	995692	4505934	9777142	2392703	128887456
AU094	14945	2755	2989	3385	2669	24791	8440	9055	8615		6681	6681	2549	8440	12308	8703	24352	14857	144329200
AU095	3941099	169231	2832440	252923	48000	236835	103385	4110505	1556044	401231	363429	1482901	641582	637451	1060396	4189275	9440263	1960176	133218328
AU096	470769	43692	437538	56615	18198	409055	29978	621714	103736	95824	69011	359736	129055	135121	227253	782769	2495868	3013275	168162352
AU097	1097407	41846	899429	65846	15912	96352	1318066	5626	442110	119385	107429	443692	216176	197890	357363	1162901	3355472	800703	135944848
AU098	4531341	156659	3122813	265934	51956	242549	96703	4197011	1717451	450374	364571	1717099	720088	660396	1246066	4435208	10470857	2105626	176067456
AU099	3998857	149626	2708484	247912	52835	221275	92980	3944527	1666374	409758	332659	1636519	684835	630066	1180747	4462506	10234989	2056352	169204016

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SampleID	N-C6	2,2-dimethyl pentane	methylcyclo pentane	2,4-dimethyl pentane	2,2,3-trimethyl pentane	benzene	3,3-dimethyl pentane	cyclo hexane	2-methyl hexane	2,3-dimethyl pentane	1,1-dimethyl cyclopentane	3-methyl hexane	1 cis 3-dimethyl cyclopentane	1 t 3-dimethyl cyclopentane	1 t 2-dimethyl cyclopentane	nC7	methyl cyclohexane	toluene	Total Area
AU100	10725	40659	2813	1934	2857	5099	6886	6813	9319		1495	2637	6593	6330	5864	15033	21275	5275	140103120
AU101	24484	2286	4747	2462	1231	3077	4308	3604	8352		6418	5099	2454	2488	6242	62681	43165	7560	137307776
AU102	6314461	239121	4258550	373011	72440	503604	129143	5867604	2499604	625670	505670	2469626	1038418	966066	1776967	5588088	14136483	2497758	183250080
AU103	4519473	224967	3304527	359297	56747	369626	110154	4652132	1922286	536879	415824	1967385	806681	741363	1411736	4382066	11355164	1914110	154597840
AU104	4460686	141275	2996571	222330	36659	635341	69538	4392791	1508923	409231	341451	1520176	682198	627253	1196923	4891692	9928088	3337319	205648880
AU105	7007209	224088	4540396	381187	68747	595165	129143	6117451	2310330	689495	503297	2375209	1007230	912967	1722549	5532308	13382944	2537318	189386240
AU106	5592264	206681	3733451	321231	53011	449231	107341	5053978	534681	2008879	432527	1982663	850549	776352	1465670	4492923	11453011	2031560	161766592
AU107	5521319	193231	3691604	324264	56352	462901	111648	4983209	2020747	568791	432703	2053275	866813	802637	1497407	4642593	11771868	2158330	163082000
AU108	5810901	226989	3528527	405099	81495	134505	128791	4107868	2328527	678242	444659	2380044	929788	849055	1605187	3961055	11257406	712703	146366960
AU109	662330	47209	591385	66374	26497	457011	44484	959385	446681	139956	139956	467692	164923	161495	282725	1087584	3581187	3518681	119321176
AU110	3549539	114462	1772835	196308	58989	49626	71736	2633143	1282637	345187	238242	1253275	491429	462857	821890	3921319	7807121	636396	138598256
AU111	2313670	89055	1198154	156132	33495	36571	62505	1880527	956044	258064	258462	957978	372161	356177	626549	2970286	6094505	463297	116469560
AU112	22242	7385	3956	6769	5099	2462	7736	2198	2110		985	2725	2374	6154	14769	5538	6769	4571	124381128
AU113	2946110	120967	2390681	186198	43165	453011	98374	3677011	1211604	356396	284659	1239033	593143	549451	1045714	3793143	8961977	2830330	128723712
AU114	86615	12571	133187	19692	6505	61011	13466	527560	282637	78857	66110	337670	166769	161846	286066	1464791	4358154	2680967	153239472
AU115	599297	26462	555604	42637	14418	132659	46418	844308	265231	77978	73231	268659	150857	133099	244835	746110	2352791	474286	125929912
AU116	1516044	69978	461714	133363	24352	7209	81934	633055	830681	197626	105758	793319	248571	234374	422418	2436132	3392879	55648	124806960
AU117	1806188	81934	726505	150066	27077	17846	47912	946813	902505	230681	140747	880264	301714	284747	501802	2577670	4241934	86769	139242016
AU118	9078505	294769	4062505	510593	86857	49846	160703	4765011	2846857	712967	500747	2642198	932395	865407	1545582	7381099	11391472	397714	177317264
AU119	1833143	57319	1394110	108835	20308	476044	38857	2303912	728000	199648	179516	736491	358330	327692	616308	2484747	5764044	2815297	118085848
AU120	4031297	149538	2573245	280797	52923	1214506	87473	3707429	1699429	382945	378989	1634462	544615	511209	917187	4270330	8692352	5570813	202149776
AU121	14505	4396	8791	4220	4747	7648	1846	2752	2637		4659	5275	2264	1758	3146	16352	9231	1802	140087168
AU122	84179	3729	60933	7329	2820	25250	4257	105254	49533	19709	11616	65015	18725	18485	30262	173492	330856	201873	89998152
AU124	631234	37438	352621	80088	31068	16344	38418	452901	432246	203672	36537	518046	139242	128834	259112	975367	236549	72281	172954672
AU125	280214	19092	394510	37587	8353	199729	20604	1152598	300246	97691	69704	334664	189192	179656	329055	1009297	6591588	3948666	165847792
AU126	351209	30066	274505	39341	17319	179956	29802	467290	315077	89495	52044	336088	89670	81495	159121	910418	1684220	1195297	125563312
AU127	1151807	40704	557798	56996	12642	190252	35576	1129110	628431	142572	84463	685621	171459	158658	311957	2628923	3281453	1735076	123302056
AU129	1443305	47002	814476	74726	13701	2476	29273	994932	558606	165890	115207	673407	247475	224696	414095	1807953	2596439	109236	157970560
AU130	956182	61767	187764	87003	19489		38515	180973	463484	180023	62640	598596	101713	93042	199297	1263174	697059	44119	146578928
AU132	4774470	136798	3173263	242426	40703	1569924	78945	6682267	1868386	432999	311206	1826887	706725	655986	1194911	6411810	17630830	8636075	294118140
AU133	1296133	47257	1582675	91447	17333	951656	39707	4561139	800664	250143	227055	805724	595923	568697	1044651	2943436	17690558	8641759	147165824
AU134	201538	10908	74926	16888	2997	4497	8622	131364	93405	26401	12550	103201	22295	21108	39759	318690	352096	246266	213951312
AU135	72162	4706	88668	8398	5018	40924	5695	164081	62540	24098	19048	72310	26374	24818	48524	197148	545284	285538	213913760
AU136	64131	3855	64301	5087	1935	40733	6509	107557	40284	14051	10696	47072	19789	18813	30005	134327	334470	205797	105044960
AU137	96713	4847	100834	9253	4081	60220	6634	182451	75156	21817	16610	82082	28086	29014	49017	224130	580312	354163	201616016
AU138	2687730	176079	1746489	232360	82453	475068	143788	2753468	1842824	489144	264502	2066099	597374	547522	1097516	5966259	10016762	3536007	364021600
AU140	1040485	25790	407535	51038	9054	0	16585	561845	378690	218979	55974	454354	153548	139121	307297	1244526	1387835	109011	92794672
AU141	403820	13244	186754	25052	3028	703	7728	32295	250425	136917	35975	309556	100340	93325	209969	950651	1078378	5843	92774320
AU142	1934	835	2330	2286	1231	3692	1319	791	5011	18286	56703	19868	10725	1739	1758	2252	4571	615	62565088
AU143	595517	12147	537374	30176	5275	7736	6753	551218	193738	159164	41655	283556	136818	118857	296048	648883	1128688	967	89874448
AU144	43165	6242	0	15648	1431	0	4456	3846	141131	27692	1319	136764	9407	10110	17846	698242	109475	3516	101477176
AU145	307329	30381	153124	45306	8908	0	19508	345785	365290	93445	37161	388634	81219	72176	156332	1018341	1349656	44044	95845640
AU146	863033	9603	412454	34599	1816	398676	9338	1217407	279308	168894	3360	314048	92764	88125	181943	1151896	1761717	552879	111248136
AU147	1744615	573978	142505	703	27385	79736	44396	591473	1111077	262154	173099	1130022	254242	220396	394901	2650462	2672440	470154	146540784
AU148	19956	7073	0	13538	879	4747	3429	2286	128979	19022	0	114061	5234	3956	8956	511385	19625	2462	103140616
AU149	17879	7209	835	12076	0	0	0	0	117935	16718	0	102622	1495	2901	8253	470945	23560	2813	98389568
AU150	2725	1495	7473	13538	1143	4308	308	2110	2022	2022	703	4308	1670	1363	1319	11253	4308	1275	87526944
AU151	2110	703	0	1407	3253	1670	1934	6945	2989	1231	3604	2989	4484	1319	9934	11429	1934	1758	89941320
AU152	2545983	82637	1937143	140484	28659	169582	72088	2868835	930901	258110	228835	929934	420308	395956	682637	2753143	6739956	1266286	163751872
AU153	496000	20484	405451	33319	8703	20659	16440	740747	232378	35978	70110	320088	133714	136703	257758	991692	2408703	478945	121124160
AU279	2697190	191356	161939	250868	77895	2628355	137648	2806227	1769655	442102	270789	1742940	412517	384480	722828	4140101	6599576	7809862	171923552
AU328	#######	518505	6490989	926242	157890	45187	297495	8025670	5809582	1359912	938198	5681670	1753055	1651077	3654066	13127032	18989890	579956	191427536
AU329	2213534	45235	798527	113407	13656	0	27842	1105172	772246	410007	111980	946010	307504	269124	616579	2589024	2753807	258725	178078768
AU338	287478	20044	154505	39473	10374	7209	12571	203165	267077	74989	33846	260396	74374	71648	146901	900967	906286	122175	228783440
AU351	1564308	82901	236308	146637	25495	15648	155165	401670	988132	275077	74286	1074286	193407	168791	353846	2719121	2249407	20484	144000000
AU352	2559584	65846	1376352	125011	24352	498989	50110	2294154	1103473	275780	158593	1216703	314725	282154	557626	3137407	4494418	2225934	143000000
AU353	1110945	78681	1229099	189538	107429	1238593	62681	2823473	726593	184440	967	717506	346374	334330	606330	2024791	8851692	7108747	195000000
AU360	3339868	214330	1981363	342593	78242	33846	135019	2539692	2155868	605890	361626	2171253	652044	610198	1171209	5342066	9364482	496289	285420930
AU362	13978	48352	144440	80264	19692	4220	40352	184879	30042	202522	157670	136703	122901	114549	160264	10110	362374	21626	253136256
AU363	4312703	242286	3786901	389363	91429	26286	176615	5967385	3077363	937407	785055	3361978	1464176	1379341	2781538	9993318	21563998	707868	304994050
AU366	2739429	195516	1575912	302637	70154	23429	121231	2065934	1888615	524835	306901	1906462	547165	507604	983912	4604220	7717363	355341	240384912

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SampleID	N-C6	2,2-dimethyl pentane	methylcyclo pentane	2,4-dimethyl pentane	2,2,3-trimethyl pentane	benzene	3,3-dimethyl pentane	cyclo hexane	2-methyl hexane	2,3-dimethyl pentane	1,1-dimethyl cyclopentane	3-methyl hexane	1 cis 3-dimethyl cyclopentane	1 t 3-dimethyl cyclopentane	1 t 2-dimethyl cyclopentane	nC7	methyl cyclohexane	toluene	Total Area
AU367	171429	11868	143297	16176	17758	35341	9758	242989	97846	32967	20659	118593	40967	35516	75077	306877	650725	192218	151019296
AU368	345231	54066	328176	65055	29890	34989	55648	685802	541802	178637	97055	634154	177143	163560	360703	1718681	3448527	884264	208083136
AU369	1068044	240703	27077	208879	86418	1143	191385	77275	1109451	360264	57670	1190593	43165	39648	192967	2122110	840615	50813	197229792
AU370	2462	103297	5407	180484	39487	2989	84044	4879	0	394901	256000	26110	51780	46330	118242	4425	316890	28396	225686096
AU374	48000	57934	387165	101011	22505	7473	49846	584000	137231	252132	203473	365626	253714	229890	397538	33776	1178374	31824	241553424
AU382	3925890	197451	1954769	286154	59692	51956	107429	2425846	2021319	453626	300220	1964527	601407	568527	1036571	5337231	8163428	561055	214534464
AU383	910769	38242	757363	54242	13451	236396	20923	1251429	369319	112703	99868	405714	191648	180044	343209	1333890	3084659	1579253	174416240
AU384	92835	5802	113143	10022	2725	47121	7824	298110	106119	41138	34022	140571	69890	67165	129846	566857	1503824	986813	181963104
AU385	1013099	45714	526506	74681	13626	3780	25055	656879	511121	146286	110418	530110	216791	198857	385407	1575100	2771297	51604	176162384
AU386	1738110	58198	1264000	90725	16308	415209	33495	1950242	642989	162198	153670	657670	292396	275604	520176	2096440	4355341	2298022	184404816
AU387	2423824	44571	1317275	83868	11692	191516	23604	2022681	662593	202549	224264	713055	364044	347165	585495	2627077	5034813	1232155	161565392
AU388	500176	23033	221714	48703	11077	13978	15385	254989	331341	89143	30330	318154	89495	83077	164044	1181978	1031780	68396	173577264
Raw Peak Areas																			

APPENDIX D

CSIA - Carbon Isotopic Signatures of n-Alkanes

Isotope ratio monitoring gas chromatography-mass spectrometry (GC-IRMS), otherwise known as compound-specific isotope analysis (CSIA) is an analytical tool using a stable isotope mass spectrometer as the real-time detector for a gas chromatograph. The interface is a combustion and/or micro reaction device which quantitatively converts individual compounds in the chromatographic effluent to gases, carbon dioxide or nitrogen, which are amenable to continuous flow isotopic analysis. The method can be sensitive to 0.5 - 5 nmole of carbon or nitrogen and, for compounds at or near natural isotopic abundances, measurements reproducible to within 0.3 or 0.4 ‰ (1 ‰ for nitrogen) are possible. The feasibility of this tool for routine natural abundance isotope measurements on individual compounds has now seen it applied to a wide range of geochemical problems including oil-source correlation.

The isotopic character of kerogen and the bulk fractions of oils has been used to infer genetic relationships between petroleum and its source sediment (e.g., Sofer, 1984; Clayton, 1991). Isotopic correlations may also provide information of the source and maturity of wet gas deposits (Schoell, 1983; James, 1990). The carbon isotopic tool is valuable in that it represents a high proportion of the carbon in effective petroleum precursors. However, it is often limited by the narrow range of values observed in local situations and does not readily allow one to differentiate co-sourcing and maturity-dependent effects. A potentially more discriminating tool is the isotopic compositions of individual components, particularly *n*-alkanes and isoprenoids (e.g. Clayton, 1991; Clayton and Bjorøy, 1994). Improving knowledge about fundamental isotopic effects associated with source rock formation, facies variation, generation and cracking is leading to a strong revival of isotopic methods for oil-source correlation. For example, it is now known that source and maturity have the largest effects on *n*-alkane isotopes with biodegradation causing minimal shifts (e.g., Summons *et al*., 1995 and references therein).

A major source effect on the isotopic composition of hydrocarbons is global secular change in the ^{13}C content of the carbon in the oceans and atmosphere. This signature is controlled by tectonism for it relates to the rates of burial and erosion of organic matter and it is inherited by inorganic and organic carbon sedimented at the particular time. It will be very diagnostic for periods at the extremes of natural variability and less diagnostic at other times. For example, there were periods of extreme ^{13}C-depletion (light carbonates and organic matter) at the end of the Proterozoic (e.g., Knoll *et al*., 1986) and at beginning of the Triassic (Magaritz *et al*., 1992; Morante *et al*., 1994). Other source controls on the isotopic composition of sedimentary organic carbon are the relative proportions of marine and terrigenous organic matter, vital effects associated with specific organisms producing the organic matter, paleogeographic and paleoenvironmental circumstances, and the nature and degree of diagenetic alteration and re-working. A thorough discussion of these issues has been made elsewhere (Hayes, 1993) although a number of the principal controls can be usefully summarised here. Oil-prone organic carbon results from selective preservation of resistant biopolymers present in the walls of

algae, bacteria and the leaf cuticles of vascular plants. Such biopolymers tend to be the dominant source of the aliphatic hydrocarbons in petroleum, and evidence from pyrolysis experiments demonstrates that the δ-values of *n*-alkanes closely match those of the TOC or of precursor kerogens dominated by recognisable algal fossils. Algal organic matter tends to be enriched in ^{13}C leading to marine and lacustrine organic carbon and derived *n*-alkanes being isotopically 'heavier' than that produced by vascular plants.

A selection of oils and condensates from the study were examined by CSIA since the methodology had the potential to discriminate liquids on the basis of their major components (i.e., *n*-alkanes) as opposed to biomarkers which are sometimes in trace levels. One potential difficulty with the analysis and interpretation stems from the vast differences in carbon number distribution between the heaviest oils and lightest condensates. It is also possible that many of the condensates comprised low MW hydrocarbons from one source mixed with smaller amounts of higher alkanes from a different source. Our approach was to adduct the *n*-alkanes from the whole oil or condensate into a 5Å molecular sieve. This was then destroyed with a mixture of HF and pentane with the released alkanes going into the pentane. Alkanes from nonadecane up to the waxes could be analysed with extra injections at higher concentration generally required to obtain data for the higher MW alkanes present as minor components of the condensates.

Our analysis of Perth Basin oils reported earlier (Summons *et al*., 1995) showed clear distinction between isotopically 'light', the Early Triassic Dongara-type oils, and the isotopically heavy Permian Whicher Range condensate and the Cretaceous Gage-Roads-1 oil. The Jurassic Walyering condensates were between these extremes (**Figure A-1**; CSIA analysis Perth Basin) with the Jurassic Gingin-1 condensate quite heavy and close to Gage Roads and Whicher Range. Thus, the CSIA analysis discriminates between the isotopically light Triassic and isotopically heavy Permian and Cretaceous lacustrine groups with variable behaviour of the Jurassic samples.

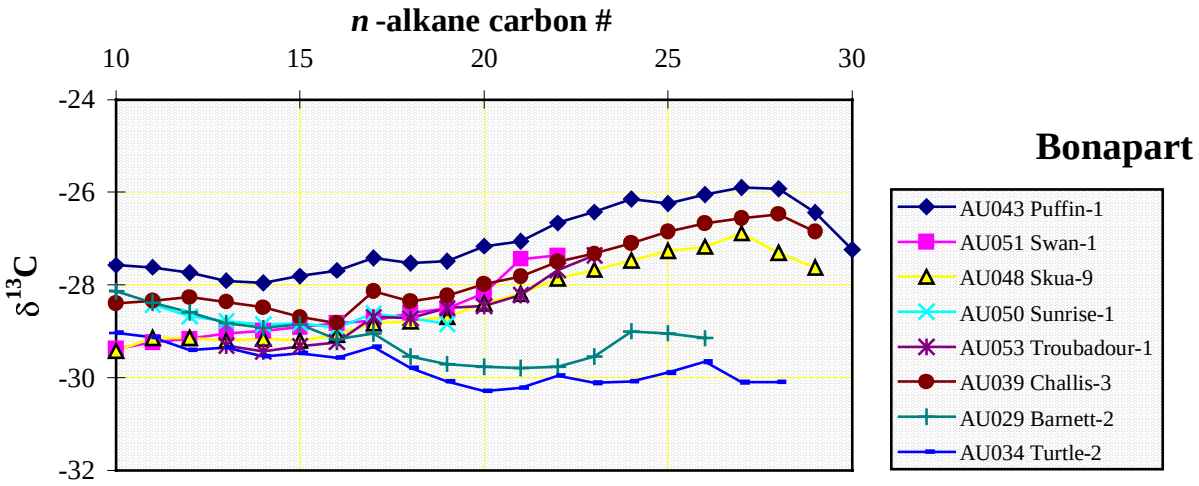
Extension of these finding to the Northwest Shelf did not yield black/white differences, as was hoped, although a number of subtle points are worthy of note and indicate potential for discrimination under some circumstances.

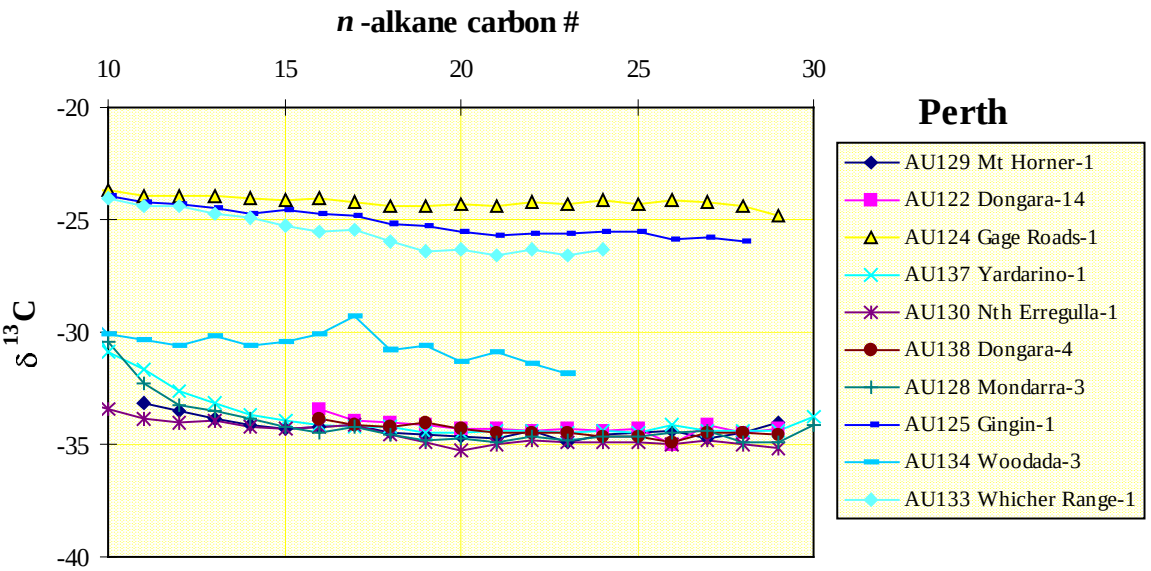
In the Bonaparte Basin, the Westralian 2 oils exemplified by Challis, Puffin, Skua and Swan show a pattern of values between -27.5 to -29.5 ‰ at the C9-15 end and becoming gradually heavier to around -26 to -27.5 ‰ at the C25+ end. In contrast, the Transitional L/G oils exemplified by Barnett and Turtle begin at values near -27 to 28 ‰ and show a subtle tend to lighter values near -30‰ at C18 then staying near this up to the C25+ end. Thus, pristine, unaltered oils from the two families could be readily distinguished by these opposing trends as shown in **Figure A-2** (CSIA analysis Bonaparte Basin).

The Perth and Bonaparte Basin findings were extended to the more complex situation in the Carnarvon. To try to simplify interpretation, we divided the data into three groups based on the Barrow-Exmouth, Dampier and Rankin Trend geographic and

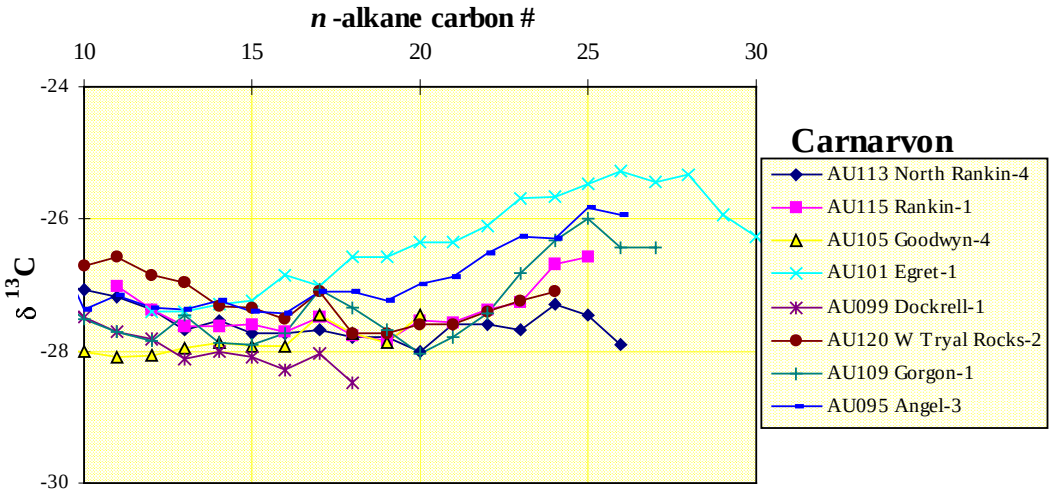
geochemical separation (**Figures A-3, A-4**, and **A-5**). We first observed that the 'stand-out' oil is Rough Range-1 (Austral 2) because of its overall heaviness and close resemblance to its system analogue, Gage Roads-1. The remaining Barrow and Dampier oils show similar behaviour to their Bonaparte (Westralian 2) analogues in getting heavier from between -26.5 to -28.5 ‰ at the C9-15 end to near -25.5 to -27.5 ‰ C25+ end. Most of the oils appear to fall within a 2 ‰ window over this general trendline.

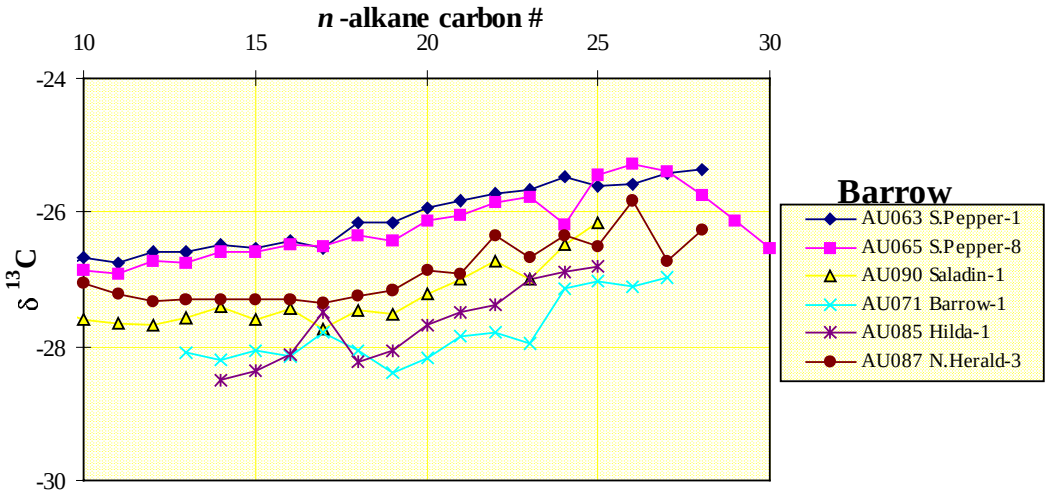
In contrast, the Rankin group show a range of behaviours. Tidelpole did not give a suitable range for diagnosis. Apart from the C9 data of Angel-3, Angel-3 and Egret-1 resemble the above Barrow and Dampier oils. Dockrell-1, on the other hand, becomes lighter from C9-16 -27 ‰ to -28.5 ‰, a trend also followed by West Tryall Rocks and North Rankin-4. The remaining condensates show a 'bowed' distribution beginning heavy, being lighter near C15-20 and becoming heavy again toward higher MW. It is clear from this range of ^{13}C values and behaviours that there is a continuum of isotopic compositions of *n*-alkanes and that this continuum could reflect multiple sources and/or maturity/facies variations within the source(s). However, combining information from the biomarkers, bulk isotopes and these CSIA data, end-members appear to be Rough Range (Austral 1), Dockrell-1 (Westralian 1), South Pepper-1 and 8 (Westralian 2B) and Harriet-B-3 or Cossack-1 (Westralian 2D). A more solid interpretation for the method will eventuate when a larger suite of samples has been analysed.

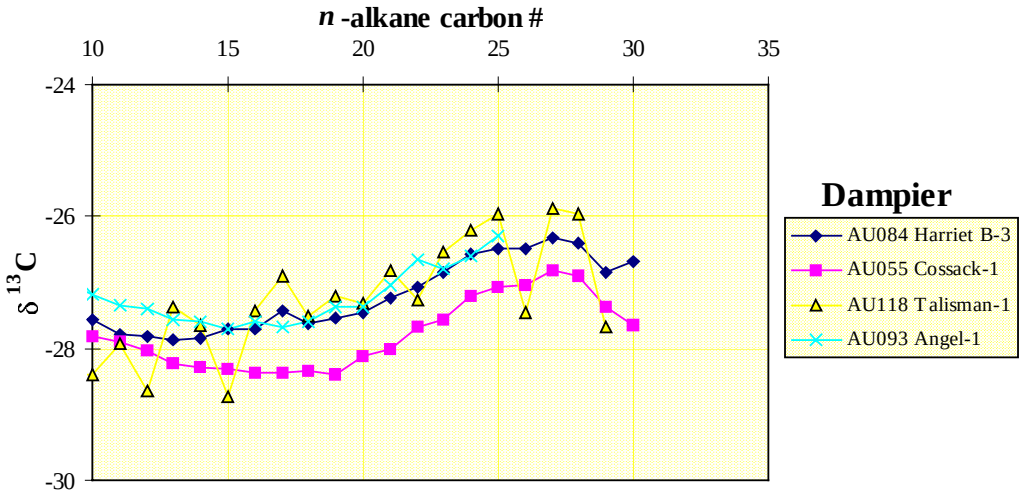




Figures A-1 and **A-2**. Perth and Bonaparte Basins: CSIA *n*-Alkane Plots.







Figures A-3, A-4 and **A-5**. Carnarvon Basins: CSIA *n*-Alkane Plots.