Bureau of Mineral Resources, Geology & Geophysics

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PETROLEUM PROSPECTIVITY OF AREA W91-1 CENTRAL BROWSE BASIN, WESTERN AUSTRALIA

by

A. J. Williams

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Abstract

Vacant Area W91-1 comprises seventeen 5' x 5' graticular blocks in the middle of the Browse Basin, approximately 400 km north of Broome, Western Australia. Water depths in Area W91-1 range from 200 m in the south to over 400 m in the northwest.

The main plays in the central Browse Basin are sandstone reservoirs in fault blocks and anticlines below and above the Middle Jurassic unconformity, and subtler structural and stratigraphic traps in the Cretaceous section. These may be charged with hydrocarbons generated in Jurassic and possibly Cretaceous source rocks.

Seismic surveying in the central Browse Basin is at reconnaissance and semi-detailed levels, with detailing over the Caswell strucure. The most recent seismic survey was in 1987. The two wells drilled in Area W91-1 - Caswell No 1 drilled in 1977-8 and Caswell No 2 drilled in 1983 - had hydrocarbon shows, and oil was recovered from a RFT of a Cretaceous sandstone in Caswell No 2.

Oil recovery within Area W91-1 and signicant gas/condensate discoveries approximately 70 km west at Scott Reef and Brecknock indicate that the area lies in a region prospective for petroleum, where further exploration is needed.

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PETROLEUM PROSPECTIVITY OF AREA W91-1
CENTRAL BROWSE BASIN, WESTERN AUSTRALIA

Introduction

This record is a summary of selected published and open file information available for the central Browse Basin, prepared as a promotional product for Area W91-1 of Offshore Vacant Area Release No 1 of 1991 (Figure 1).

Basin setting

The Browse Basin lies entirely offshore. It extends from near the coast to beyond the 1000 m isobath, underlying an area of approximately 105 000 km^2 northwest of the Precambrian Kimberley Block. The basin contains over 12 000 m of sediments, which range in age from Permian to Recent. Reviews of the basin include those by Crostella (1976), Allen & others (1978), Passmore (1980), Forrest & Horstman (1986), Willis (1988) and Elliott (1990).

Area W91-1 comprises seventeen 5′ x 5′ graticular blocks in the central part of the basin, underlying water depths of 200 m in the south to 400 m in the northwest (Figure 1). It is located approximately 400 km north of Broome, Western Australia.

Previous exploration

Geophysical exploration began in the Browse Basin in 1963 when Woodside (Lakes Entrance) Oil Co Ltd and Mid Eastern Oil NL conducted a reconnaissance airborne magnetic survey. The first seismic survey was in 1964. The first seismic survey in Area W91-1 was undertaken in 1969, the latest in 1987. These, and the intervening surveys, give semi-detailed coverage with some detailing over the Caswell structure. Data quality is only poor to fair in the early seismic surveys, but improved in the later ones. Willis (1988) indicated that the major problems affecting seismic acquisition and processing in the Browse Basin are caused by the wedge of Tertiary carbonates which thickens offshore.

Two wells have been drilled in Area W91-1: Caswell Nos 1 & 2. Oil was recovered from an Upper Cretaceous sandstone in Caswell No 2.

Structure

The Browse Basin is bounded to the east by the Precambrian Kimberley Block and to the west by the Scott Plateau (Figure 2).

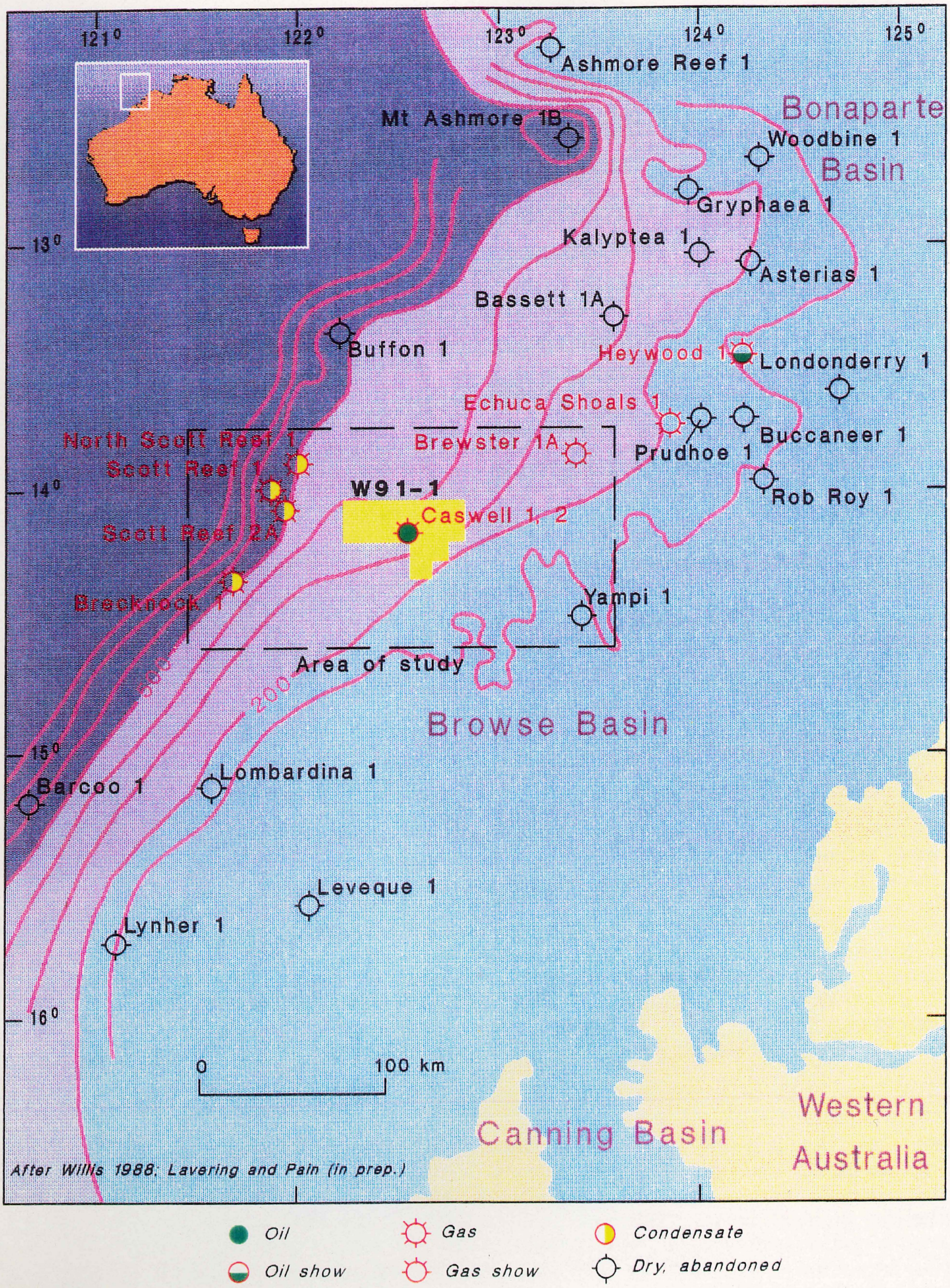

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Figure 1. Location map: Browse Basin, showing the area of study and Vacant Area W91-1 (17 blocks).

Its northern boundary with the Bonaparte Basin lies along the southwestern margins of the Ashmore Platform, Vulcan Sub-basin and Londonderry High, and its southern boundary approximately along the southwestern margin of the Leveque Shelf. However, the boundaries with the Bonaparte Basin to the north and the Canning Basin and Rowley Sub-basin to the south and southwest are not clear cut. The major structural trends of the Browse Basin have a northeasterly orientation.

Structural elements

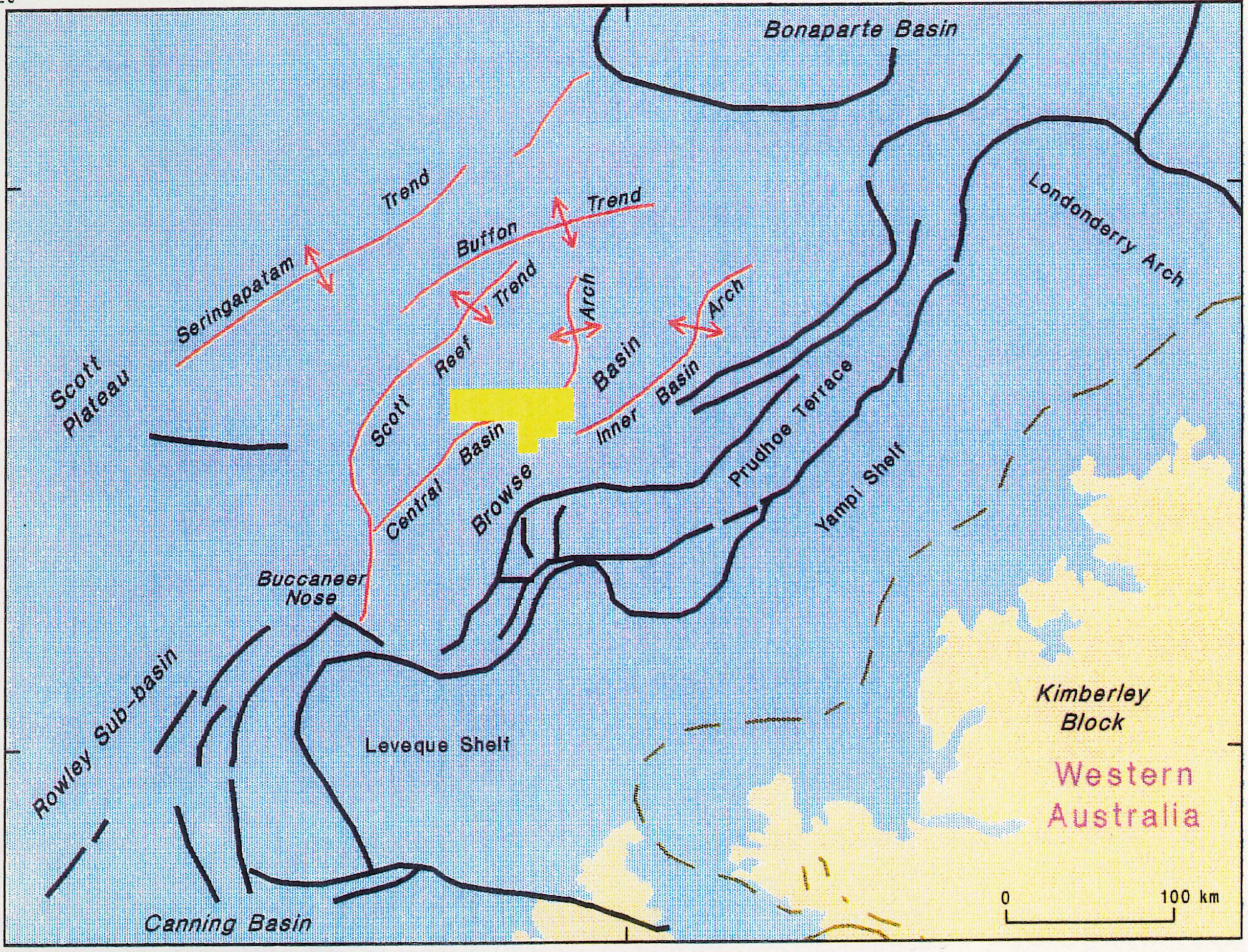
The Scott Plateau underlies an area between the 1000 and 3000 m isobaths and is one of several mid-slope plateaux off the western margin of Australia (Stagg 1978). It is considered by some authors as a subsided part of the Browse Basin (Elliott 1990). Its boundary with the main part of the Browse Basin lies west of the Scott Reef structural trend.

The Yampi Shelf is a wide shelf of shallow basement, which extends west from the Precambrian Kimberley Block and has a veneer of Cenozoic and Cretaceous sediments. It links north and south with the Londonderry Arch and Leveque Shelf. The Prudhoe Terrace occurs at the west side of a series of northeast trending 'down to the basin' faults forming a hinge line with the Yampi Shelf; a similar series of major faults marks the boundary of the Prudhoe Terrace with the main part of the Browse Basin. The Prudhoe Terrace comprises steeply dipping basement, and Palaeozoic horst blocks overlain by Jurassic and younger sediments (Allen & others 1978).

The complexities of the structural trends underlying the central part of the basin and influencing later structural growth have yet to be fully elucidated. Two major faulted arches - the Inner and Central Basin Arches - related to Early Mesozoic periods of tectonism, are shown as sinuous, broadly northeasterly trending features (Figure 2). The similar, sub-parallel Scott Reef and Buffon Trends mark the western limit of the central part of the basin with its thick pile of Cretaceous and Tertiary sediments. Beyond the Scott Reef Trend to the Seringapatam Trend these sediments thin, and the Jurassic and Triassic section appears to be restricted to the inner part of the Scott Plateau. The southern extension of the merged Scott Reef Trend and Central Basin Arch is the north trending Buccaneer Nose.

Structural evolution

Bradshaw & others (1988) consider that, although it may be underlain by older sediments, the Browse Basin was initiated as an intracratonic basin in the Late Carboniferous to Early Permian during an early phase of extension associated with the breakup of Gondwana. In the Late Permian there was block faulting along the eastern margin of the basin and uplift on the northwestern edge of the Scott Plateau. Older sediments may be preserved in grabens formed by this tectonism (Powell 1976; Forrest & Horstman 1986). There was a marine transgression across the basin in the Early Triassic followed by a Middle Triassic regression and the deposition of thick fluvio-deltaic sediments.



After Woodside 1978; Willis 1988
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Figure 2. Structural elements

The intracratonic phase (Figure 3) ended with a major tectonic episode related to rift formation at the end of the Triassic, which resulted in significant block faulting and left the Scott Plateau emergent with the central, rifted, part of the Browse Basin lying between it and the Kimberley Block. This tectonic phase continued, with another major rifting episode in the Browse Basin in the Middle Jurassic. The Late Triassic and Middle Jurassic tectonism caused the major northeasterly structural trends in the basin which comprise elongated fault blocks segmented by transverse faults. Rift infill sediments were derived from the Kimberley Block and the Scott Plateau. Middle to possibly early Late Jurassic volcanics, which have been related to incipient sea floor spreading west of the Scott Plateau, were extruded in the Browse Basin and the Scott Plateau. A basinwide unconformity developed at this point gives rise to the 'Jb' seismic marker (Figure 3), and for convenience is termed the 'Jb' Unconformity. (Crostella 1976; Powell 1976; Forrest & Horstman 1986; Willis 1988; Elliott 1990).

No major tectonic episodes affected the Browse Basin subsequent to the Middle Jurassic event. Pattillo & Nicholls (1990) considered that the onset of sea floor spreading in the Indian Ocean occurred in the mid-Valanginian rather than Oxfordian as had previously been generally accepted. Although this event corresponds to an intra-Valanginian disconformity in the Vulcan Sub-Basin, the corresponding section in the Browse Basin closely approaches conformity. Marine transgressions combined with progressive subsidence of the Scott Plateau through the Late Jurassic and Early Cretaceous resulted in deposition spreading onto the basin margins and high-standing blocks. In the Late Cretaceous and through the Cenozoic, open ocean circulation was established with the foundering of the Scott Plateau and the tilting of the continental margin. Minor movements focussed along pre-existing features occurred during these periods, including gentle folding on the outer flanks of the basin. Such movements as did occur may prove to be important in trap formation - as, for example, the intra-Kimmeridgian tectonism in the adjacent Vulcan Sub-basin (Pattillo & Nicholls 1990) - but have yet to be detailed. (Crostella 1976; Allen & others 1978; Forrest & Horstman 1986; Willis 1988).

An Oligocene/Miocene tectonic episode resulted in further rejuvenation of some structures, and there are some indications of strike-slip movement along the northwestern margin of the Leveque Platform. (Stagg 1978; Forrest & Horstman 1986); Willis 1988).

Stratigraphy

Descriptions of the stratigraphy of the Browse Basin have lacked formally defined rock units, and sediments have been assigned to age, 'series' or 'sequence' units defined by seismic horizons (Allen & others 1978; Willis 1988; Elliott 1990). Lavering & Pain (in prep) have applied rock unit names from the Bonaparte Basin to Browse Basin stratigraphy - mainly at Group level. Figure 3 attempts to integrate these approaches, but a more detailed synthesis of Browse Basin stratigraphy is needed.

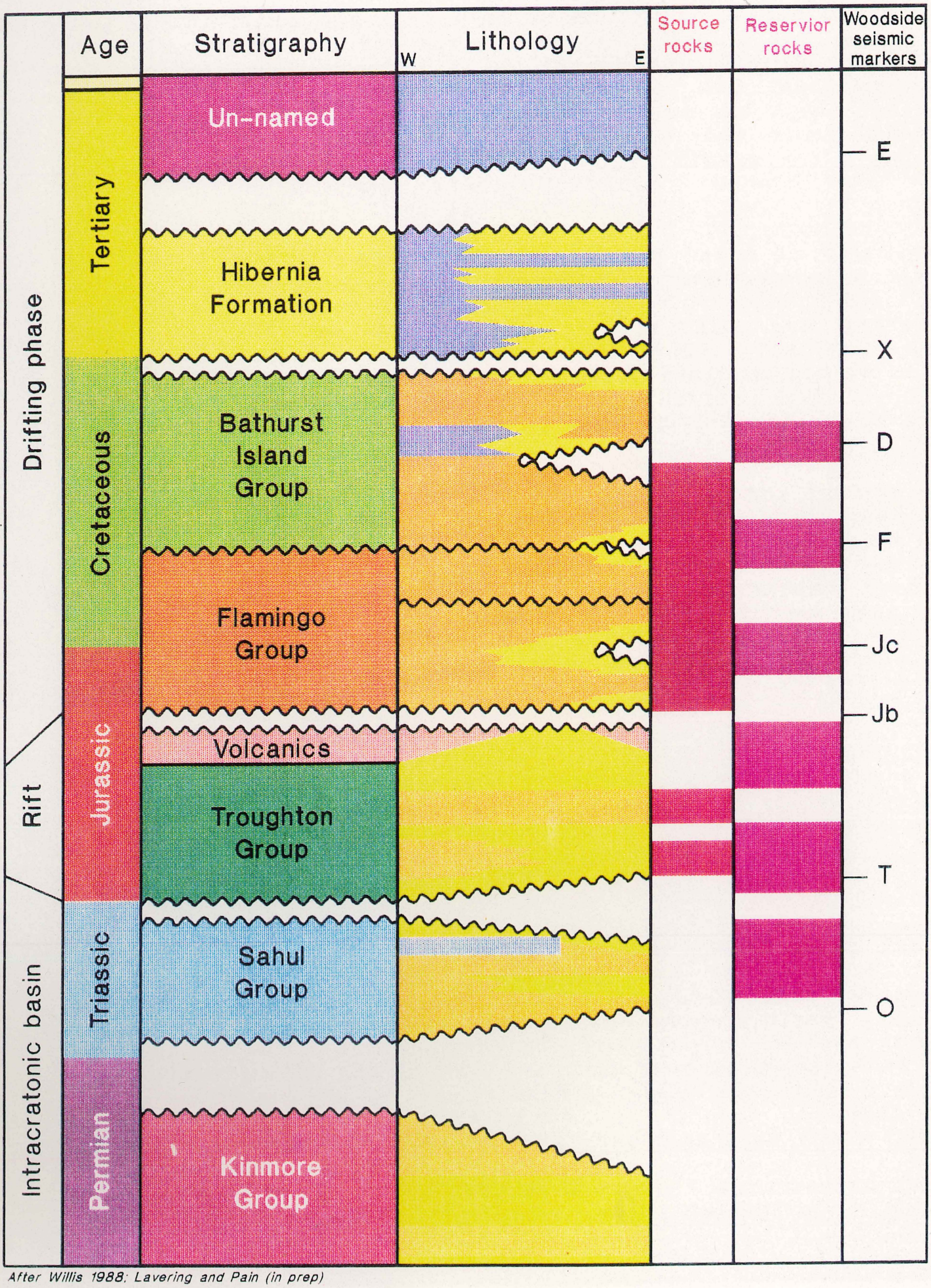


Figure 3. Stratigraphic column

Browse Basin

The following stratigraphic description is taken from Lavering & Pain (in prep).

"The Browse Basin was initiated as an intracratonic basin in the Late Carboniferous to Early Permian, during an episode of extensional fault movement prior to the main Mesozoic breakup of Gondwana. Upper Carboniferous deltaic and shallow marine sediments are present on the Prudhoe Terrace and Yampi Shelf (Rob Roy No 1 well), and seismic data indicate that older Palaeozoic sediments are present beneath the central Browse Basin and Scott Plateau (Allen & others 1978; Bradshaw & others 1988; Stagg 1978).

The entire Permian sequence in the Browse Basin is likely to be similar to that in the Carnarvon, Canning and Bonaparte Basins - predominantly clastic with glacial or glacio-marine facies at the base, overlain by shallow marine, deltaic and terrestrial sandstone and shale sequences (Lavering 1985). The Upper Permian Mount Goodwin Formation along the eastern basin margin is thin and comprises marine claystone and siliciclastics. It wedges out towards the east, as indicated by seismic and well data (Willis 1988).

The Triassic Sahul Group unconformably overlies the Permian on the eastern side of the basin. As elsewhere on the North West Shelf, a thick sequence of marine claystone of Scythian to Anisian age is also present. A fluvio-deltaic sequence of Carnian and Norian age developed along the eastern margin of the Browse Basin. A regressive sequence of the same age in the northern part of the basin comprises a basal sequence of shelf carbonate and shale which grades upwards into deltaic sandstone and shale. The western part of the basin contains Late Ladinian marine shelf claystone and limestone, overlain by deltaic clastics and dolomite.

The Lower and Middle Jurassic Troughton Group overlies a major unconformity surface on top of faulted Triassic and older sequences. It was deposited as a rift-fill sequence of fluvio-deltaic to marginal marine sandstone, shale, claystone and carbonate in areas of active subsidence.

Block faulting and volcanism in the late Middle Jurassic terminated rift-fill deposition. This was succeeded by the Upper Jurassic Flamingo Group which comprises deltaic and fluvial sandstones. To the west, the sandstones grade into marine shale and volcanics which overlie part of the Ashmore Block. The Upper Jurassic sequence onlaps a major unconformity surface thoughout the basin which is particularly evident over major basement highs. While sedimentation of the Flamingo Group commenced during the Oxfordian in subsiding depocentres, on 'highs' and shelf areas sedimentation did not commence until the Tithonian (Mory 1988).

Cretaceous open marine conditions were well established from the Valanginian to Aptian, as evidenced by the deposition of greensand

and radiolarian, glauconitic and calcareous claystone which comprise the basal part of the Bathurst Island Group. These lithofacies were deposited on an extensive marine shelf with low clastic sediment supply. The western part of the Ashmore Platform was emergent during this period.

Widespread deposition of marine siltstones and claystones occurred during the Albian to Maastrichtian. Concurrently, a calcareous marine shelf formed on the outer basin margin as the level of clastic input declined, but in the central basin and northwards into the Vulcan Sub-basin up to 2000 m of fine clastic sediments were deposited (Mory 1988). During the Campanian to Maastrichtian, a series of lenticular sandstone bodies were deposited northwards from the Yampi Shelf into the Vulcan Sub-basin and on the Ashmore Block. Mory (1988) considers these sandstone units to be possibly subtidal.

By the Early Cainozoic the basin had developed into a carbonate shelf on the outer margin with interbedded sandstone units shorewards in the central and eastern parts of the basin. The Cainozoic sequence ranges in thickness from 200 m in the east to over 3000 m in the Scott Reef No 1 well to the west.

In the Oligocene, uplift and consequent erosion occurred over much of the eastern part of the shelf and continued carbonate sedimentation was restricted to the outer part of the shelf area. During the Late Cainozoic, subsidence on the outer shelf increased and resulted in deposition of thick prograding wedges of carbonate. The outer limits of the Late Miocene shelf are currently in water depths of up to 1000 m, except in the vicinity of large reef complexes such as Scott Reef where reef growth has kept pace with the rate of subsidence (Willis 1988)."

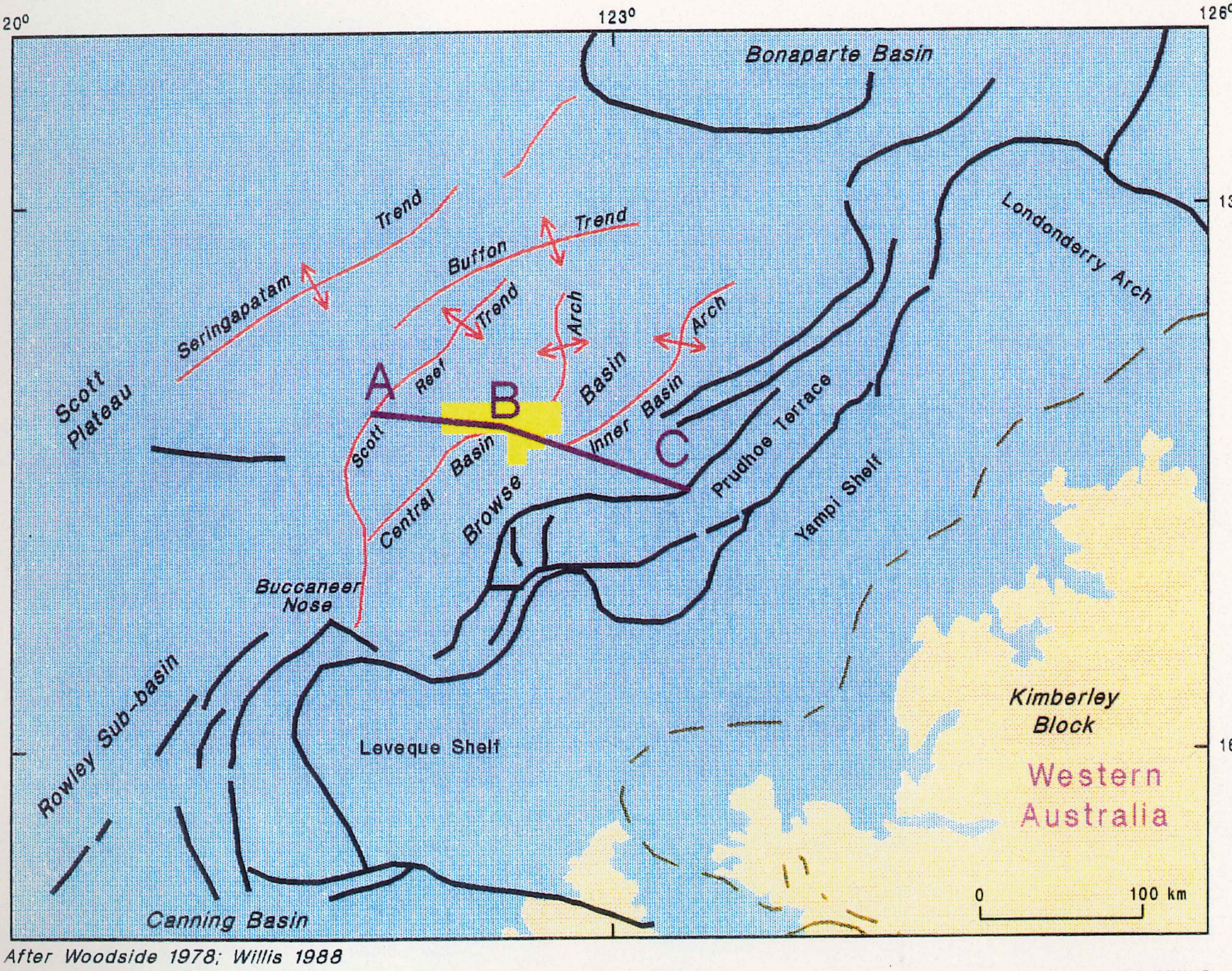
Study area - central Browse Basin

The stratigraphy in and near Area W91-1 is generalised on a cross-section through the Yampi No 1, Caswell Nos 1 & 2 and Scott Reef No 1 wells (Figures 4 & 5).

Yampi No 1 drilled 406 m of sediments assigned a Lower Permian age. These comprise sandstones - some dolomitised - siltstones and claystones, with minor dolomite.

The Triassic section in Yampi No 1 is also a clastic sequence, predominantly sandstones with interbedded claystones and minor siltstones. Scott Reef No 1 and North Scott Reef No 1 intersected Upper Triassic limestones, dolomites and claystones, but Triassic sediments are too deeply buried to have been intersected by wells drilled in the central part of the study area.

Lower to Middle Jurassic sediments underlying the Callovian 'Jb' Unconformity were penetrated by all deep wells in the study area except Caswell No 1. These sediments overly the Triassic in angular unconformity (Willis 1988). They are continental to fluvial-deltaic and near shore sandstones and claystones, with minor limestones in the Scott Reef wells. In Area W91-1, Caswell No 2 penetrated 47 m of this sequence comprising sandstone,



After Woodside 1978; Willis 1988

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Figure 4. Location of cross-section in Figures 5 and 11.

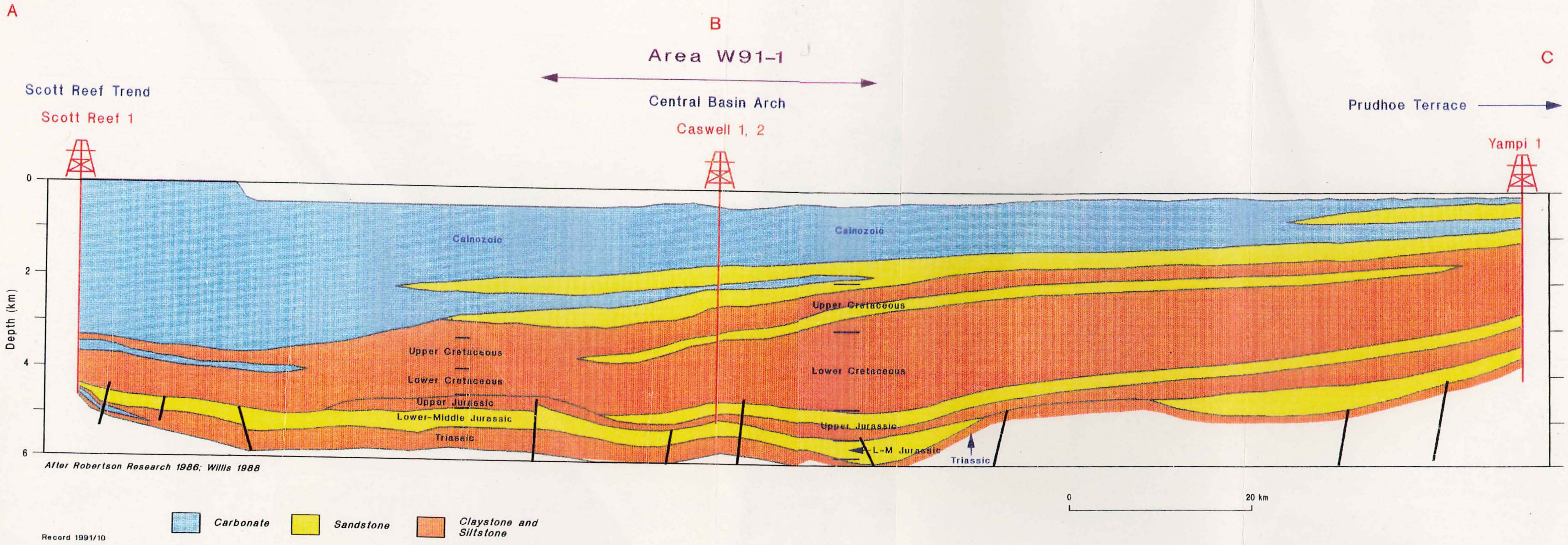

Figure 5. Schematic cross-section: Scott Reef 1 - Caswell 1, 2 - Yampi 1.

siltstone and minor coal. To the east, at Yampi No 1, the sequence is predominantly sandstone. The sequence is interpreted to have a maximum thickness of approximately 3500 m in the southern part of the basin (Elliott 1990).

Middle Jurassic volcanics were penetrated by Yampi No 1 (86 m) and in Scott Reef No 1 were encountered interbedded with other sediments over an interval of 114 m. They were not seen in the Caswell No 2 well under Area 91-1.

The upper Middle to Upper Jurassic sequence is predominantly deltaic to marginal marine, with increasing marine influences upwards through the section (Robertson Research 1986), and has a maximum thickness of more than 770 m (Elliott 1990). At Caswell No 2, in Area W91-1, it is 448 m thick and comprises interbedded sandstones, siltstones and claystones, with minor coal. It is approximately 700 m thick with similar lithologies at Yampi No 1, but is thin or absent along the Scott Reef Trend.

The basin became progressively more open to marine influence through the Early Cretaceous, and marine clastic sediments - predominantly fine grained - were deposited in the central Browse Basin and onlap the Yampi Shelf. Lower Cretaceous sediments are generally thin or absent over the Scott Reef Trend, but have a maximum penetrated section of 781 m of claystone with minor siltstones in Scott Reef No 2A, although the sequence is absent at North Scott Reef No 1. It is 1089 m thick in the central part of the basin in Caswell No 2, where again it comprises predominantly marine claystones, in part grading to siltstones, with only very minor sandstone. The greatest thickness penetrated is 1629 m at Brewster No 1A (Elliott 1990). Eastwards towards the shelf, at Yampi No 1 the sequence is 1021 m thick and contains greater but still relatively minor amounts of sandstone interbedded with claystones.

Fully oceanic circulation was established in the Late Cretaceous, with hemi-pelagic carbonates deposited across the outer and much of the central parts of the Browse Basin (Willis 1988). The maximum thickness of Upper Cretaceous sediments penetrated is 822 m at Caswell No 2. At Yampi No 1 the Upper Cretaceous is over 500 m thick. The sequence again thins over the Scott Reef Trend where it is less than 200 m thick. The sediments in the lower part of the sequence are claystones and siltstones at Yampi No 1 in the east, grading to claystones and marls and calcilutites at Caswell Nos 1 & 2 and in the Scott Reef wells in the central and western parts of the study area. In the upper part of the sequence, sandstones are present in the central and eastern part of the study area. In Yampi No 1 these are interpreted as continental and strandline deposits (Elliott 1990). Sandstones in the more basinally positioned Caswell wells are interbedded with marls and claystones. Westwards and across the Scott Reef Trend, marine carbonates were deposited.

In the Cenozoic, the basin depocentre moved from the central to the western part of the basin. A complex, prograding carbonate wedge formed together with reef complexes (as seen in the Scott Reef wells). Eastwards the carbonates interdigitate with thick sandstones derived from the basin margin. Underlying Area W91-1 in the Caswell wells, sandstones are interbedded with carbonates in the lower part of the Tertiary but the upper part of the sequence comprises entirely carbonates.

Wells

Two wells have been drilled in Area W91-1, Caswell Nos 1 & 2. Six wells drilled near Area W91-1 are also discussed below. Scott Reef No 1 discovered a gas/condensate accumulation, the delimitation of which was extended by the Scott Reef No 2A and North Scott Reef No 1 wells. Brecknock No 1 discovered a gas/condensate accumulation. Brewster No 1A was not tested but a significant gas accumulation was interpreted from logs, and hydrocarbon shows were recorded in Yampi No 1. Good oil shows were reported from Caswell Nos 1 & 2 wells and an RFT in Caswell No 2 recovered oil. Lavering & Pain (in prep) present details of all hydrocarbon accumulations encountered in the Browse Basin.

Drilling problems in the Browse Basin relate mainly to lost circulation zones in Tertiary carbonates and sandstones, and to clay swelling and overpressures in Cretaceous claystones (Willis 1988).

Caswell No 1

Caswell No 1 was spudded on 9 August 1977 in 345 m of water and reached a total depth (TD) of 4089 m subsea on 2 January 1978.

Caswell No 1 was drilled on a northeast trending drape anticline over a pre-'Jb' Unconformity horst block in the Central Basin Arch. Anticlinal closure was interpreted for both pre- and post-unconformity objectives. The section drilled comprised approximately 1300 m of Tertiary carbonates overlying 1800 m of Upper Cretaceous sandstones, carbonates and claystones, and 700 m of predominantly claystones of Early Cretaceous age.

Lost circulation occured at 1654 m subsea at the boundary of Tertiary carbonates and sandstones. Hole conditions deteriorated while drilling the predominantly claystone Upper Cretaceous section and mudweight was increased moderately; lost circulation occurred in sandstones and carbonates in this part of the section. Further lost circulation occurred while controlling a kick at 3599 m subsea. Overpressured Lower Cretaceous claystones were then drilled to TD, which was short of the objective Jurassic and Lower Neocomian sandstones. Two repeat formation test (RFT) runs were made.

Free oil in the mud was recorded while drilling Albian sandstone between 3598 and 3603 m subsea. There was no recovery on RFTs. (Woodside 1978; Willis 1988).

Caswell No 2

Caswell No 1 was spudded in 344 m of water on 1 April 1983 and reached a TD of 4983 m subsea on 28 October 1983. It was located

260 m east-southeast of Caswell No 1. The well had the same objectives as Caswell No 1. Two sidetracks were necessary - these were kicked off at 2645 and 4802 m subsea. Three RFT runs were made.

Eight hundred cubic centimetres of 47° API oil and 0.6 m^3 gas were recovered from an RFT at 3248.8 m subsea in a 4 m thick Campanian sandstone - a shallower and younger sand than that with the good oil show in Caswell No 1. Significant shows were logged in Lower Cretaceous claystones between 3879-3888 m subsea and 4053-4057 m subsea in intervals corresponding to fining upwards cycles on the gamma ray log - oil was noted in the mud over the deeper interval. Caswell is regarded as an uneconomic and undeveloped oil accumulation. (Woodside 1984; Lavering & Pain - in prep).

Scott Reef No 1

Scott Reef No 1 was spudded in February 1971. It was drilled in 50 m of water and reached a TD of 4721 m subsea on 26 May 1971.

The well was the first drilled on the northeast oriented Scott Reef structural trend. It was drilled on the southern culmination of a complex structure at 'Jb' Unconformity level. The structure is fault bounded to the northwest and dip closed in other directions, with 2 culminations and other, more minor, faults. The well drilled a very thick (>3000 m) carbonate section before encountering Cretaceous and Jurassic regional claystone seals over the hydrocarbon bearing Lower to Middle Jurassic and Triassic section. Reservoirs are sandstones and sandy dolomite.

Scott Reef No 1 well suffered lost circulation in Tertiary carbonates; tight claystones were encountered in the Lower Cretaceous section. Three formation interval tests (FITs) and 4 drillstem tests (DSTs) were carried out.

Gas and condensate were recovered, with the best DST flow rate being 0.52×10^6 m^3 GPD and 57.9 m^3 CPD. Twenty-four metres of net sand pay was interpreted in the Lower to Middle Jurassic section. The Scott Reef accumulation is classified as subeconomic and undeveloped. (BOC 1971; Willis 1988; Bint 1988; Lavering & Pain - in prep).

Scott Reef Nos 2/2A

Scott Reef No 2 was spudded on 18 April 1977. A mechanical problem with the hole opener caused the well to be plugged and abandoned after reaching 288 m subsea.

Scott Reef No 2A, located 4.4 km southeast of Scott Reef No 1, was spudded on 27 April 1977 in 55 m of water. It reached a TD of 4272 m subsea in August 1977. The well was sited down dip and separated by a fault from Scott Reef No 1.

Lost circulation occurred in Tertiary carbonates, with minor losses in Jurassic volcanics. Hole conditions deteriorated in the Upper Jurassic shale section. Six FITs were run.

Only trace to minor amounts of hydrocarbons were recovered, and the well is considered to have penetrated a long gas/water transition zone in in the Lower to Middle Jurassic section. (Woodside 1977; Willis 1988; Bint 1988).

North Scott Reef No 1

North Scott Reef No 1 was spudded in February 1982 in 442 m of water and reached a TD of 4763 m subsea on 6 May 1982. It was located 20 km northeast of Scott Reef No 1. The well was drilled on the northern culmination of the Scott Reef structure, and penetrated Lower to possibly Middle Jurassic and Triassic sediments in the objective section. No lost circulation was reported. Two RFTs were run and a production test carried out.

Sixty-six metres of net gas pay were interpreted in Lower Jurassic sandstones. The production test of this interval yielded a flow rate of 1.27×10^6 m^3 GPD and 79 m^3 CPD. (Woodside 1982; Bint 1988).

Brecknock No 1

Brecknock No 1 was located approximately 42 km south-southwest of Scott Reef No 1, in 543 m of water. It was spudded on 31 July 1979 and reached a TD of 4289 m subsea on 9 November 1979.

Brecknock No 1 was drilled on the Scott Reef Trend to investigate a pre-'Jb' Unconformity horst block, with overlying sediments forming a drape anticline. Like the Scott Reef wells, it penetrated a thick sequence of Tertiary carbonates above a predominantly claystone Cretaceous section, before reaching the main objective Jurassic section.

Circulation was lost in Tertiary carbonates. Thirty RFTs and a DST were undertaken.

Gas and condensate were recovered from RFTs of Lower to Middle Jurassic sandstones; water and solution gas were recovered from the DST. Sixty-eight metres of gas sand have been interpreted in Lower to Middle Jurassic sandstones. The Brecknock accumulation is classified as subeconomic and undeveloped. (Woodside 1980; Bint 1988; Lavering & Pain - in prep).

Brewster Nos 1 & 1A

Brewster No 1 was spudded on 13 May 1980 and plugged and abandoned 3 days later due to mechanical problems after reaching a TD of 655 m subsea.

Brewster No 1A was spudded on 23 May 1980 in a water depth of 256 m and reached a TD of 4695 m subsea on 8 December 1980.

The feature drilled by Brewster No 1A lies along the Inner Basin Arch. It comprises anticlinal drape over two convergent horst blocks in the pre-'Jb' Unconformity section. Objectives were sandstones in the Jurassic sections above and below the unconformity. The well penetrated approximately 1000 m of Tertiary carbonates and 1000 m of Upper Jurassic and Cretaceous sandstones before drilling nearly 2000 m of predominantly fine grained Cretaceous clastics sealing the objective section.

Lost circulation occurred in the Tertiary carbonate section and in Upper Jurassic sandstones. The hole was sidetracked due to mechanical problems after the drill string became differentially stuck at 4456 m subsea. Two RFT runs were made, one of which had to be abandoned due to mechanical failure.

Hydrocarbon - probably gas - bearing sandstones were interpreted in the Jurassic section. Nine RFTs were made but no hydrocarbons were recovered, possibly due to plugging of the tool. (Woodside 1981; Willis 1988).

<u>Yampi No 1</u>

Yampi No 1 was spudded on 3 June 1973 in 91 m of water, and reached a TD of 4163 m subsea on 17 September 1973.

Yampi No 1 was sited just basinward of the Prudhoe Terrace to investigate an easterly trending faulted anticline at Permo-Triassic level. Post-drill interpretation is that the mapped objective appears to be the 'Jb' Unconformity, and that there is no structural closure.

Tight hole problems considered to be caused by abnormally pressured claystones were encountered in Upper Jurassic and Lower Cretaceous sections. Four succesful FITs were conducted.

No hydrocarbons were recovered, although there were shows and traces of residual oil in a core and log interpreted possible residual hydrocarbon saturations in Middle Jurassic sandstones. (BOC 1974; Willis 1988).

Reservoirs & seals

Potential reservoir rock intervals are summarised on Figure 3. They lie in Jurassic, particularly Upper Jurassic, and in Cretaceous units.

<u>Triassic (Sahul Group)</u>

Triassic sediments below 4352 m subsea are reservoirs for gas/condensate in the Scott Reef accumulation. In the section penetrated by Scott Reef No 1, the only reservoir quality units are dolomites and dolomitic sandstones which have intergranular and vugular porosity of up to 17%. In North Scott Reef No 1, Triassic sediments were predominantly limestones with an average porosity of 5%. It is unlikely that Triassic sediments will be shallow enough to be considered objectives in Area W91-1. (BOC 1971; Woodside 1982).

Lower to Middle Jurassic (Troughton Group)

This sequence has been a major target for exploration in the Browse Basin (Willis 1988). Reservoirs comprise sandstones deposited in fluvio-deltaic to nearshore marine depositional systems, with intraformational seals, and Upper Jurassic or Lower Cretaceous shale seals at the 'Jb' Unconformity.

The sequence is the main reservoir unit for the Scott Reef and Brecknock gas/condensate accumulations, and an interpreted gas accumulation at Brewster No 1A and an oil show at Heywood No 1.

Sandstones are very fine to coarse but predominantly very fine to medium grained, clean to often silty, moderately to well sorted. They are interbedded with micaceous and occasionally carbonaceous siltstones, and shales. Willis (1988) attributes the wide variation in porosities in these Lower to Middle Jurassic sandstones to a combination of the original depositional fabric, and later diagenesis which includes porosity reduction by the formation of quartz overgrowths. In the vicinity of Area W91-1, porosities in the Troughton Group range up to 19%. Core porosities in Yampi No 1 were measured at 5 to 8% between 3160 and 3165 m subsea in a sandstone/shale interval that lacked permeability. In Brecknock No 1, average sandstone porosities range from 15 to 17% between 3821 and 3977 m subsea, with permeability calculated as 220 to 283 md from a DST in the deeper part of that interval. In North Scott Reef No 1 porosities range 10 to 14% between 4113 and 4276 m subsea, and between 4325 and 4374 m subsea in Scott Reef No 1 they are between 8 and 19%, and mainly in the range 11 to 14%. Porosities in Caswell No 2 are low, ranging from 4 to 11% - mainly under 6% - below 4489 m subsea, and permeabilities are very low. (Woodside 1971, 1980, 1984; BOC 1974; Lavering & Pain - in prep).

Thus, although porosities could be enhanced over those recorded in Caswell No 2 by such factors as marginally shallower burial, variation within sandstone facies or preservation within a hydrocarbon accumulation, reservoir quality is likely to be a significant risk in this sequence underlying Area W91-1

Upper Middle Jurassic to Cretaceous (Flamingo & Bathurst Island Groups)

Fine grained clastics, calcilutites and marls predominate in this interval, but there are significant developments of sandstone, particularly in the older part and in the central and eastern parts of the study area, and shows and minor hydrocarbon recoveries are recorded.

The early part of this sequence includes alluvial, deltaic and marine shelf sediments, with more open marine sediments in the younger part of the section.

Upper Jurassic to lowermost Cretaceous sandstones are a major objective in the Browse Basin. In the vicinity of Area W91-1 these sandstones are very fine to coarse but mainly very fine to fine grained, poor to well sorted, in part argillaceous, occasionally glauconitic, with nil to minor silica and calcite cements. In Brewster No 1A and Caswell No 2, porosities range respectively from 7 to 12% and 6 to 17% between depths of approximately 4000 to 4500 m subsea - this interval is interpreted as gas bearing in Brewster No 1A (Woodside 1981, 1984). Although relatively deeply buried under Area W91-1, these sandstones have the potential to constitute a primary exploration objective. They are sealed intraformationally and by the Cretaceous part of the section which has a low sandstone/shale ratio and in effect provides a regional seal.

Lower Cretaceous sandstones generally occur as relatively thin units. Most are very fine to fine grained, well sorted, glauconitic, in part argillaceous, with various amounts of silica and calcite cement. A considerable range of porosities have been recorded from wells near Area W91-1. In Yampi No 1 porosities between 1819 and 1884 m subsea are 17 to 20%, and below 2353 m subsea are 5 to 13%. Visual estimates of 5 to 15% porosity were made between 3342 and 3367 m subsea in Brewster No 1A. In Scott Reef No 1, a sandstone between 4020 and 4068 m subsea has porosities calculated at 3 to 12%. Porosities of 7 to 17% were calculated for a sandstone between 3598 and 3603 m subsea in Caswell No 1; abundant free oil in the mud was reported while this interval was drilled. (BOC 1974; Woodside 1978, 1981).

Some of these Lower Cretaceous marine sandstones may fit a model of shelf sediments in the east and mass flow or fan sediments to the west. Wonders (1988) considered that there was evidence fitting a submarine fan model for reworked, relatively fine grained clastics in the Albian interval in the Scott Reef wells - the updip limit of which could be the thin sandstone with a good oil show in Caswell No 1 - and possibly also for Aptian sandstones (Figure 6).

Thin sandstones occur in some wells in the open marine Upper Cretaceous section which is dominated by claystones, calcilutites and marls.

In Brewster No 1A and Caswell Nos 1 & 2 wells, Campanian sandstones are very fine to fine grained while younger Campanian and Maastrichtian sandstones are very fine to granule but mainly fine to coarse grained. The sandstones are generally slightly slightly glauconitic to glauconitic. Porosities range from poor to good. In Caswell No 2, porosities in sandstones between 3162 and 3197 m subsea average 22% and in the 5 m sandstone at 3248 m subsea porosity averages 18% - 47° API oil was recovered in an RFT of this latter sandstone. In the Caswell wells these sandstones are sealed vertically by significant thicknesses of claystone and marl. (Woodside 1978, 1981, 1984).

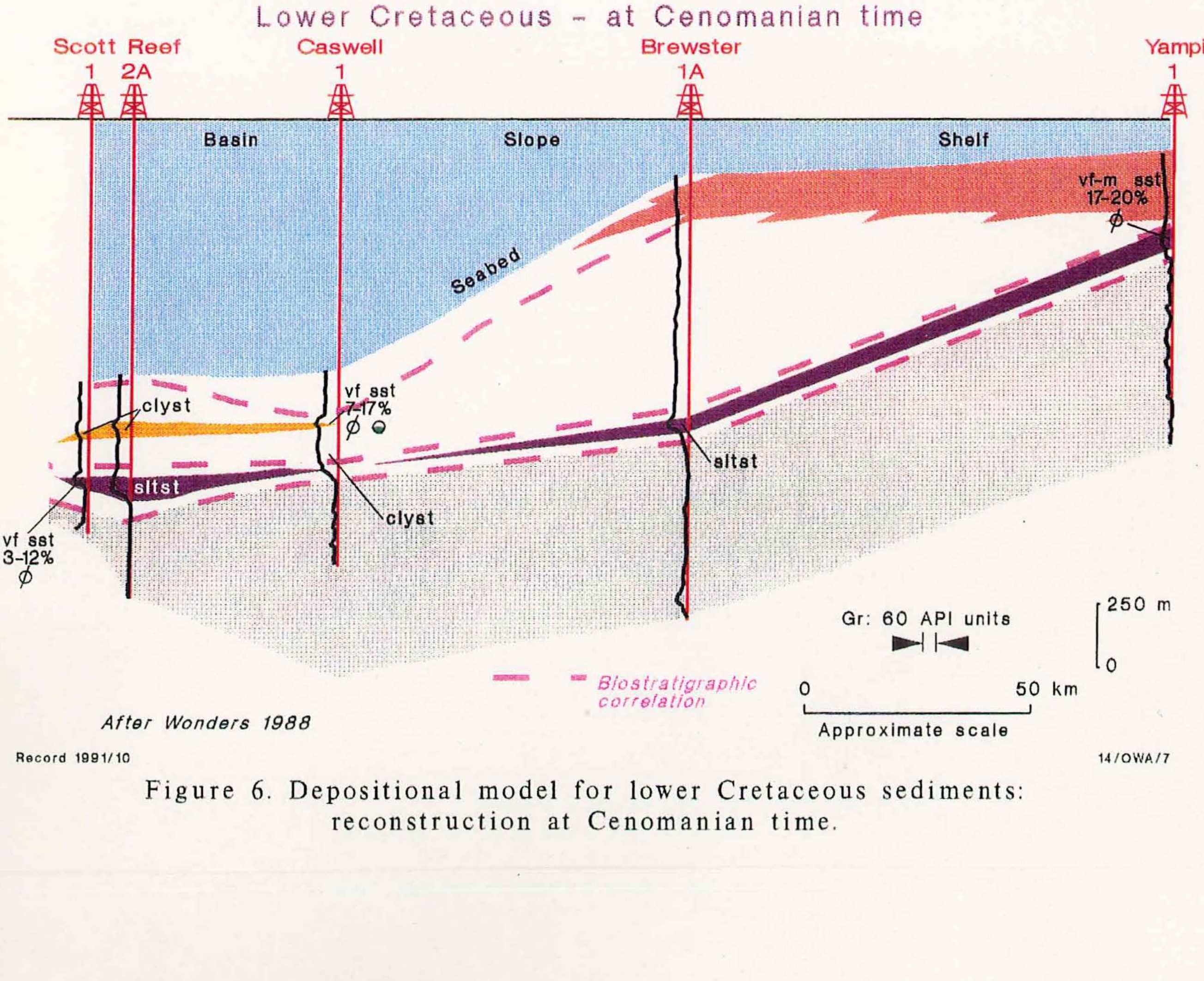

Figure 6. Depositional model for lower Cretaceous sediments: reconstruction at Cenomanian time.

Cretaceous sandstones form excellent potential reservoirs, with potential for stratigraphic as well as structural trapping, but they may be thin and require careful mapping and modelling for prediction of their distribution.

Tertiary

Excellent quality potential reservoirs exist in sandstones and some carbonate sediments in the uppermost Cretaceous and Tertiary section but, although some fine grained sediments and tight carbonates are present, a high risk is attributed to potential seal integrity.

Source rocks & maturity

Source rocks:

Robertson Research (1986) included analyses of some Browse Basin wells in a study of the geochemistry of the North West Shelf. The study did not identify any major source rock intervals in the central Browse Basin, but did conclude that the main source potential was in the Middle Jurassic and probably in Upper Jurassic sections.

In the Robertson Research (1986) study, abundance and type of kerogens were related to depositional environments to assist in mapping of source rock potential. Within Jurassic deltaic sequences of the Browse and Bonaparte Basins delta plain sediments were determined to be generally poor source rocks with some thin gas prone intervals in the lower delta plain. These intervals are richer in oil prone macerals in the lowermost delta plain and upper delta front. Good oil prone source rocks were identified close to the delta front in thick interdistributary bay and minor channel fill sediments, although these are less rich in the central Browse Basin than further north - this was determined to be due to more dynamic delta front environments in the Browse Basin. Prodelta shales were considered to generally organic rich with a range of kerogen types and with potential to contain good oil source rocks.

Although there are few data points for Lower Jurassic sediments, projection from facies mapping indicates that they may have some source potential in the middle part of the central Browse Basin. Good Middle Jurassic source rocks with oil generative potential - mapped as Vitrinite/Waxy organic facies (Figure 7) - are considered exist in lower delta plain to delta front sediments extending south from the Vulcan Graben along the eastern side of the Browse Basin as far south as Lynher No 1, and possibly fringing the postulated land mass to the west. Upper Jurassic prodelta sediments are likely to contain mainly gas prone source rocks in the eastern part of the Browse Basin - Inertinite/Vitrinite organic facies - but a more oil prone facies richer in waxy and sapropelic macerals is postulated to extend in a south-southwesterly direction through the central-western part of the Browse Basin (Figure 8). This facies is considered to be a

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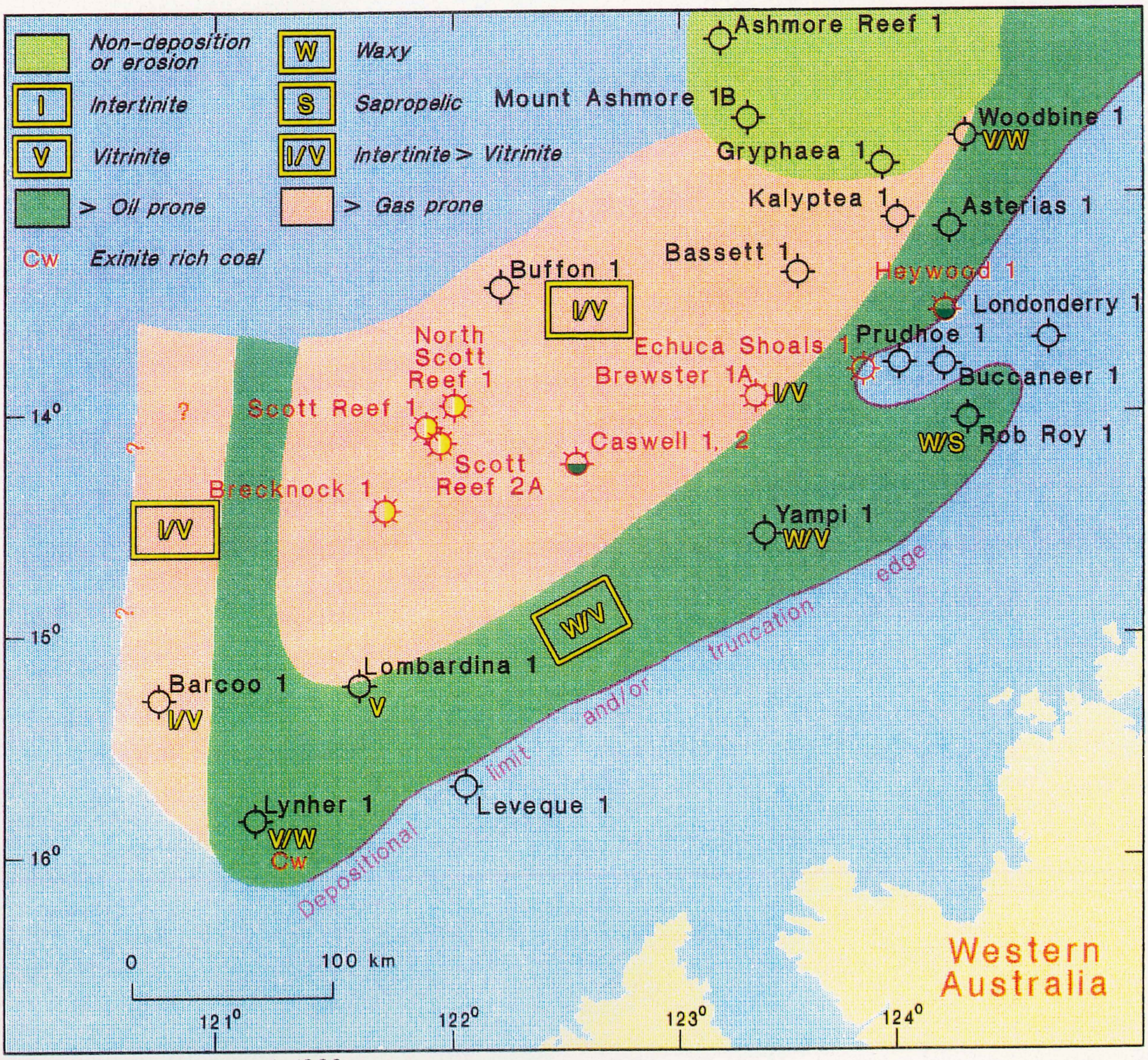

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Figure 7. Middle Jurassic (Troughton Group) kerogen facies.

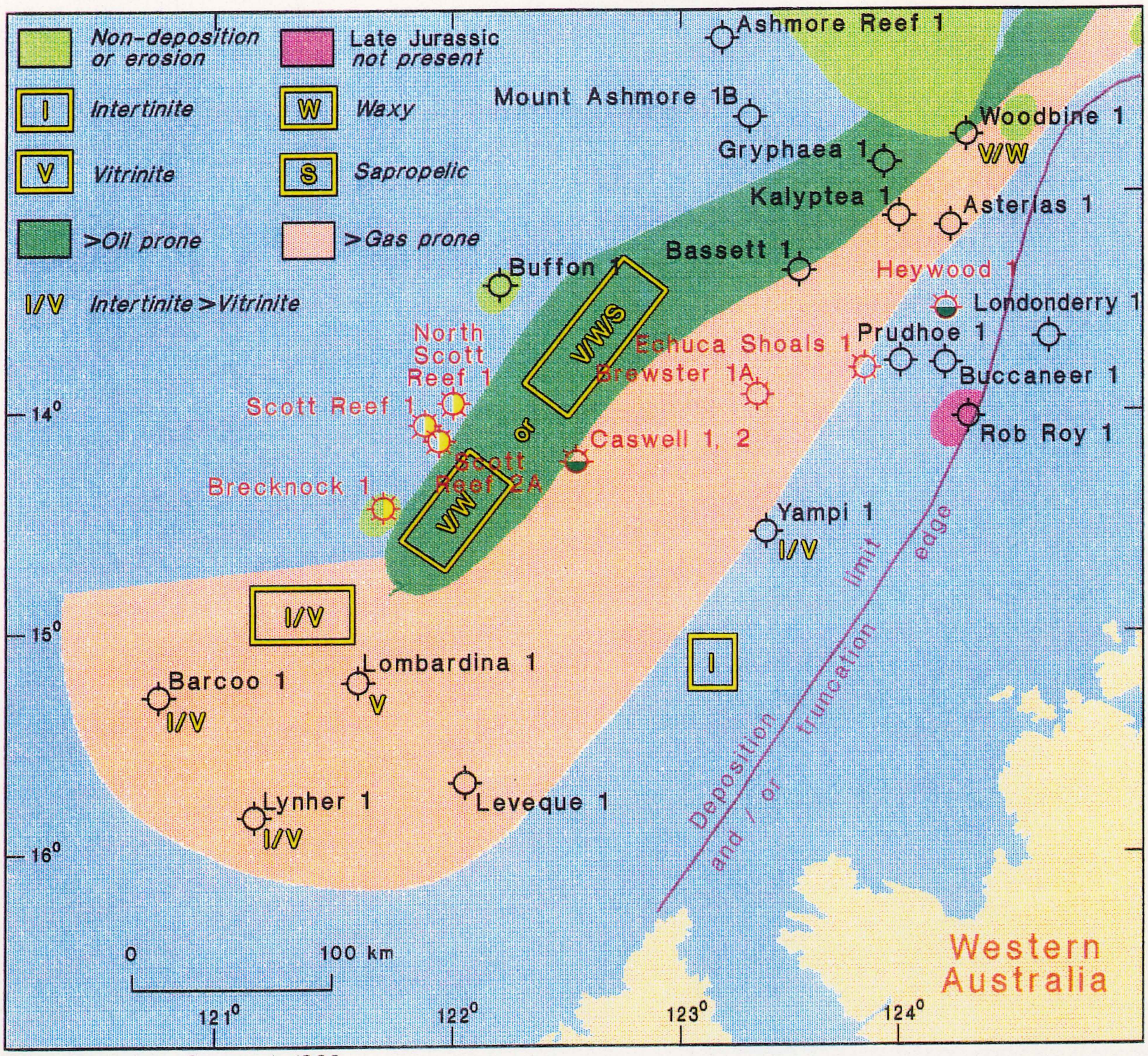

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Figure 8. Upper Jurassic - Lower Neocomian (Flamingo Group) kerogen facies.

significant source rock interval in the Vulcan Graben (Robertson Research 1986).

The Robertson Research (1986) study did not identify source rocks in the Cretaceous section except for thin, organically rich, oil prone sections in the Barcoo No 1 and Lombardina No 1 wells in the southern Browse Basin. As with other parts of the section in the central Browse Basin, this should not be taken to demonstrate that good source rocks are lacking - well spacing and sampling intervals mean that studies published to date represent an early stage in the cataloguing of source rocks in the area. Wonders (1988) indicated that in the Aptian-Albian the Browse Basin may have been a silled basin with restricted circulation and the development of anoxic conditions. If this spanned times of high planktonic productivity, good source rocks may have developed.

Willis (1988) illustrated the results of total organic carbon (TOC) analyses on over 200 sidewall cores from Browse Basin wells. Triassic samples had very low levels of TOC, avaraging less than 1%, indicating a lack of significant source potential. Lower Jurassic to Lower Cretaceous samples yielded TOC averages of over 1%, and although all results were less than 4%, this indicates - depending on the organic matter type present - that much of the section has sufficient amounts of organic matter to be a potential source of hydrocarbons. Willis (1988) also reported that other geochemical analyses of the samples show the dispersed organic matter is close to kerogen type III. Willis (1988) did not specifically identify oil source rock intervals, although significant amounts of hydrocarbons could be generated from thick intervals of the category of source rock he describes. A comparison may be made with MacDaniel's (1988) description of the most important source rocks in the western Bonaparte Basin which include oil prone Upper Jurassic claystones in and near the Swan Graben (north of the Browse Basin) with 1 to 2% TOC and hydrogen index values approaching 200 - which, depending on maturation levels, is likely to indicate kerogen type III or II-III (Tissot & Welte 1978). These may not be greatly dissimilar to some of the source rocks analysed by Willis (1988).

Maturity

Both Willis (1988) and Robertson Research (1986) agree that most of the Jurassic and Lower Cretaceous sediments in the central Browse Basin are mature for hydrocarbon generation, although there are minor differences in their mapping.

In the Robertson Research (1988) study, organic maturity is mapped in terms of spore colour index (SCI) measured on a scale of 1 to 10. Although oil generation begins at SCI 3.5, effective migration is unlikely until SCI 5.0 is reached. The effective oil window is taken as SCI 5.0 to 8.5. The major source rocks are likely to be in the Middle to Late Jurassic section which reaches a thickness of over 2500 m, for example near Brewster No 1A. Mapping at 'Jb' Unconformity (Middle Jurassic) and Lower Neocomian levels illustrates that this section is mature underlying Area W91-1 and over most of the Browse Basin, although maturity levels decrease to the south (Figures 9, 10). Much of the Cretaceous

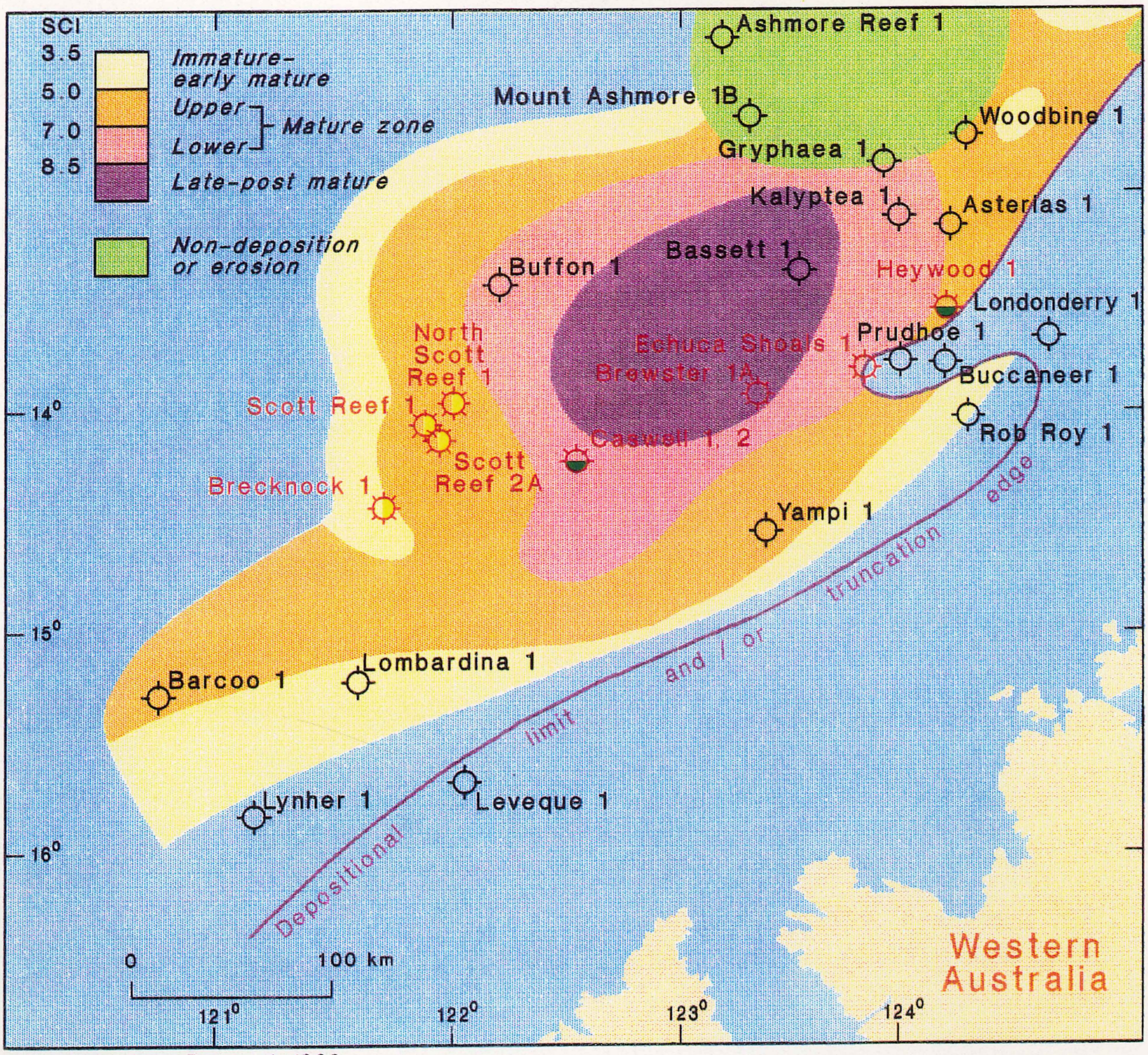

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Figure 9. Organic maturity on Middle Jurassic ('Jb') Unconformity.

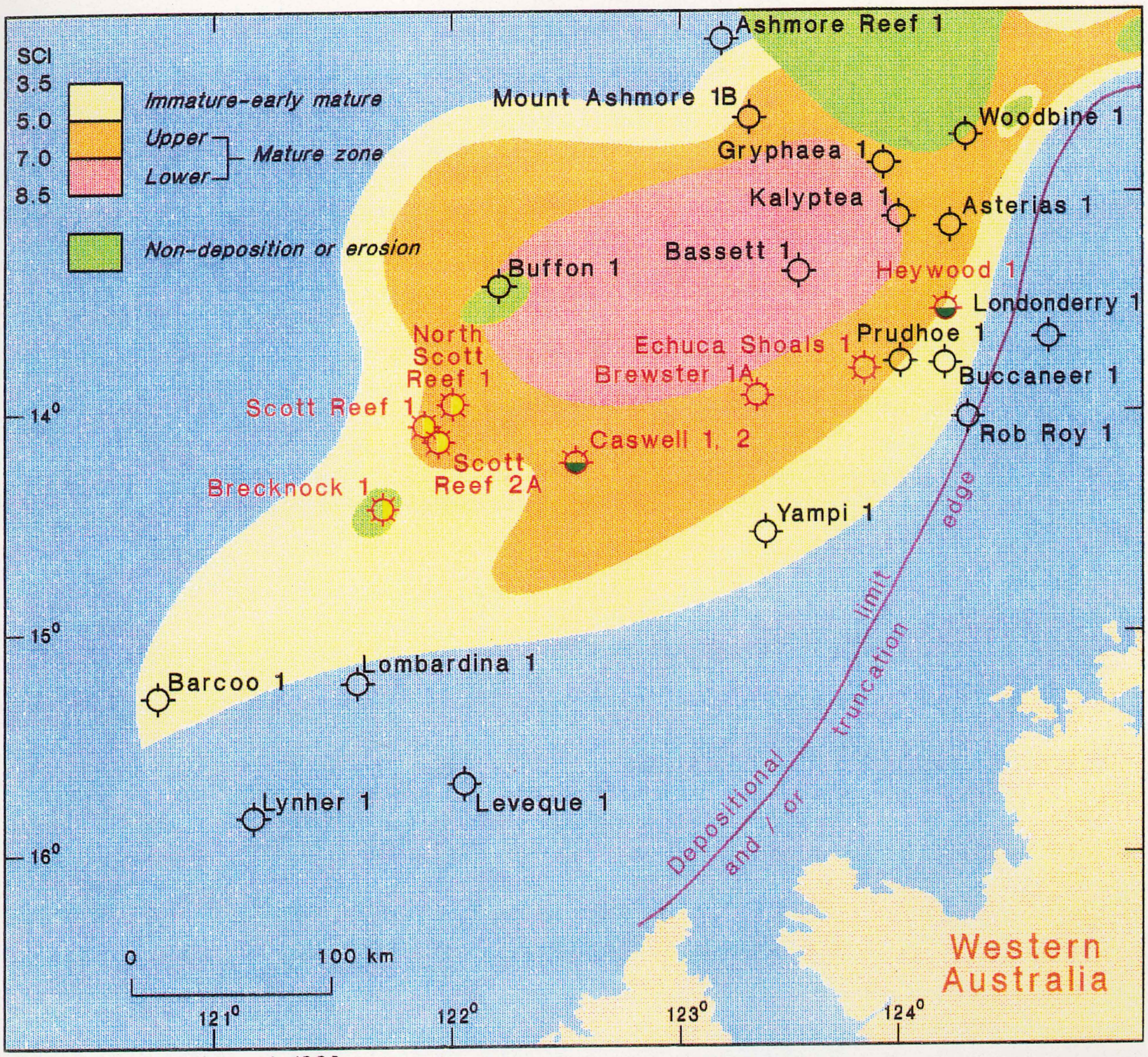

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Figure 10. Organic maturity on lower Neocomian horizon.

section has also reached the upper part of the oil window, particularly in the western part of the central Browse Basin - this is also borne out by Willis (1988) and Horstman (1988). Approximate maturity levels are also illustrated on the central Browse Basin cross-section (Figure 11).

In the central Browse Basin, significant hydrocarbon generation from Lower Jurassic source rocks probably commenced in the Lower Cretaceous. Middle Jurassic rocks entered the oil window during the Late Cretaceous, with the main pulse of generation occurring during the Miocene. Generation from Upper Jurassic and Lower Cretaceous source rocks commenced in the Tertiary. (Robertson Research 1986). Willis (1988) concluded that generation from the Lower to Middle Jurassic section commenced in the Late Cretaceous to Tertiary and that generation from Jurassic and Cretaceous source rocks is continuing.

Oil-source rock correlation indicates that the condensate in the Scott Reef accumulation is derived from a Middle or Upper Jurassic source (Robertson Research 1986).

Hydrocarbon prospectivity

The Browse Basin has non-commercial hydrocarbon reserves estimated at 486×10^9 cubic metres (17.2×10^{12} cubic feet) of gas, 23.3×10^6 kilolitres (147×10^6 barrels) of LPG and 31.6×10^6 kilolitres (199×10^6 barrels) of condensate (BMR 1990). Lavering & Pain (in prep) catalogue the gas/condensate, gas and oil discoveries that have been made in the Browse Basin - the oil discovery is a small recovery at Caswell No 2. The major discoveries are at Scott Reef and Brecknock, and are classed as subeconomic and undeveloped. Lavering & Pain (in prep) calculate the exploration drilling density in the basin as 0.2 wells/1000 km^2 - a very sparse level of exploration drilling which is illustrated by Figure 1.

Identified hydrocarbon accumulations attest to the effectiveness of generation and migration in the Browse Basin, including underlying and adjacent to Area W91-1. The distribution and quality of source and reservoir rocks is still inadequately mapped due to the sparse well control. However, mature source rocks exist in the Jurassic section and possibly in the Lower Cretaceous. Porosity and permeability retention may be a problem in deeply buried potential objectives below the 'Jb' Unconformity in Area W91-1, but the risk is less in upper Middle to Upper Jurassic sandstones and in the Cretaceous section. Sandstone thickness and sandstone/shale ratios are greater in the Jurassic interval than in the Cretaceous, and Jurassic sandstone intervals are prone to being more confidently mapped.

The most common structural trap type in the Browse Basin is drape anticlines - which may be faulted - over block faulted and folded Triassic to Middle Jurassic sequences. Most such traps have been modified by rejuvenation of faults and regional northwest tilting of the basin from the Late Cretaceous onwards (Willis 1988). Other structural traps may have been formed in less well documented post

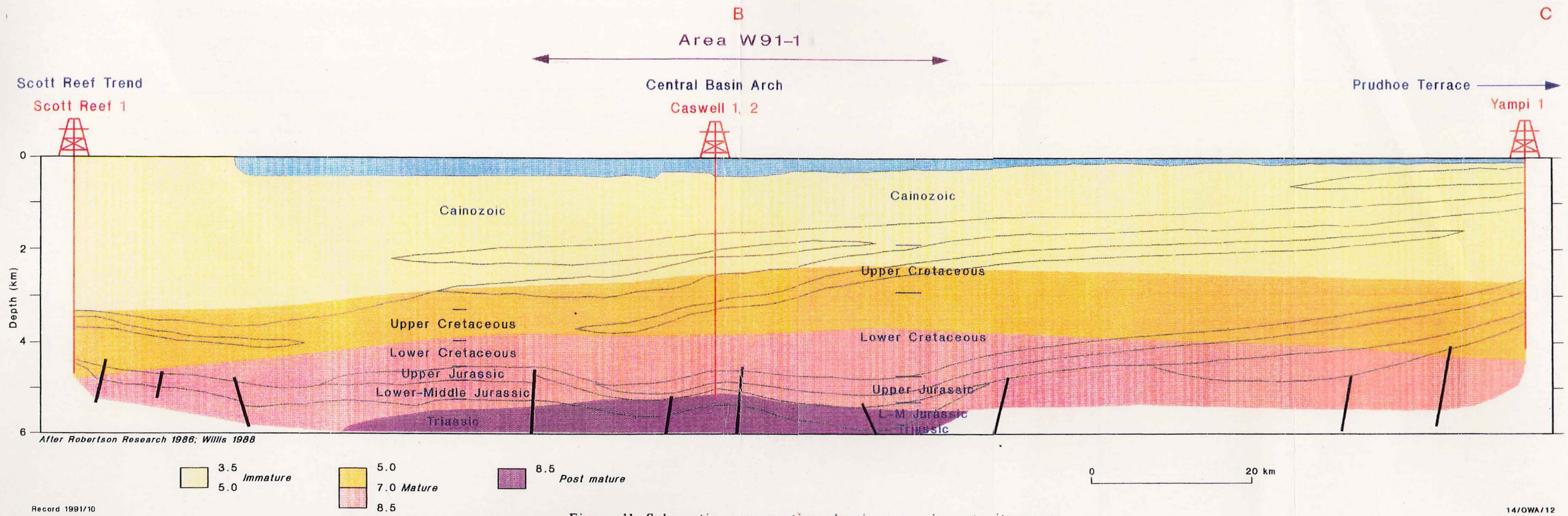

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Figure 11. Schematic cross-section showing organic maturity zones.

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Middle Jurassic tectonic episodes, such as are important in the Vulcan Sub-basin (Pattillo & Nicholls 1990). In Area W91-1, Caswell No 2 was drilled to test Jurassic sands above and below the 'Jb' Unconformity in a large, north trending, faulted drape anticline (Woodside 1984). It was positioned on an easterly flexure on the Central Basin Arch (Figure 2) which is subparallel to marked flexures in the margins of the Yampi Shelf and Prudhoe Terrace that presumably relate to an underlying tectonic grain crossing the generally northeasterly tectonic trends. Faults in the Caswell anticline mainly reach up to the 'Jb' Unconformity, but some have been rejuvenated and reach as high as the 'Jc' seismic horizon and one cuts well into the Cretaceous section. (Woodside 1984; Middleton 1988).

There is potential for stratigraphic trapping in the section, particularly in Cretaceous sandstones - there could be a stratigraphic component to the oil recovery in Caswell No 2 and the oil show in Caswell No 1. Pursuit of such opportunities underlying Area W91-1 will need careful modelling and possibly the application of 3D seismic techniques.

The timing of hydrocarbon migration and trap formation in the central Browse Basin is very good. Significant generation from the main potential source sections postdated deposition of the Cretaceous claystones that seal by overlying or enclosing reservoirs in structural or stratigraphic traps, and postdated most, if not all, trap formation.

Area W91-1 spans the Central Basin Arch, and is underlain by a thick pile of Mesozoic rocks that include proven source and reservoir sequences. Oil was recovered from a Cretaceous sandstone in Caswell No 2. Evaluation of the potential of Area W91-1 is likely to involve a review of the mapping of the original objectives of Caswell Nos 1 & 2 and of the show and recovery intervals, but plays in the area may be generalised as:

(1) Fault blocks and faulted anticlinal closures below and immediately above the 'Jb' Unconformity, sourced from and sealed by overlying and onlapping Middle to Late Jurassic shales, and possibly also sourced from deeper sediments.

(2) Drape and faulted anticlines incorporating Upper Jurassic to lowermost Cretaceous sandstones interbedded in source rock and seal sediments, and overlain by Cretaceous claystone seals.

(3) Cretaceous sandstones interbedded in source (as yet unproven) and seal rocks in stratigraphic traps, and in subtle structural and structural-stratigraphic traps that may be related to deeper Jurassic structure or possibly to independent structures created in relatively young tectonic episodes - these traps may also be sourced from the Jurassic kitchen.

The main risks are porosity retention at deeper levels, and definition of sand distribution and development and application of correct depositional and trapping models at shallower horizons.

Good shows and the recovery of oil from the 2 wells drilled in Area W91-1 are an incentive for more detailed study and exploration of the area.

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